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Documentation of Sensory Information in the Operation of Unmanned Aircraft Systems

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16. Abstract

For manned aircraft, the presence of multi-sensory inputs is a given. Pilots of manned aircraft might not even be aware of the availability of several different types of sensory inputs occurring at the same time. However, it is likely that each type of input has a reinforcing effect on the others that allows for a rapid diagnosis and response of both normal and unusual events in the cockpit. The situation for the pilot of an Unmanned Aircraft System (UAS) is much different. UAS pilots receive information regarding the state and health of their aircraft solely through electronic displays. This report includes a comparison of manned sensory information to sensory information available to the unmanned aircraft pilot, a review of remediations for sensory deficiencies from the current UAS inventory, a review of human factors research related to enhancing sensory information available to the UAS pilot, and a review of current FAA regulations related to sensory information requirements. Analyses demonstrated that UAS pilots receive less and fewer types of sensory information, compared with manned aircraft pilots. One consequence is the enhanced difficulty for UAS pilots to recognize and diagnose anomalous flight events that could endanger the safety of the flight. Recommendations include the incorporation of multi-sensory alert and warning systems into UAS control stations.

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INTRODUCTION

Under the strategy to establish standard procedures and guidelines for general aviation operators is an initiative to develop policies, procedures, and approval processes to enable the operation of unmanned aircraft systems (UASs) in the National Airspace System (NAS). UASs are a growing presence in the NAS, serving such functions as surveillance, monitoring, and research. At present, UAS operations in the NAS require special approval from the Federal Aviation Administration (FAA). They are not able to "file and fly" like manned aircraft because unique characteristics of UASs potentially present safety hazards that have not yet been fully identified.

One obvious difference between UASs and manned aircraft is that the pilot control interface (i.e., the cockpit) has been separated from the aircraft. This separation has immediate consequences for the pilot in terms of the types and quality of sensory information available. Sensory information, in this paper, is defined as information about the state and health of the aircraft that can be gained through the various human sensory modes. A human sensory mode is one of several physical processes that allows a human to receive inputs from the environment. For example, the UAS pilot typically cannot hear the engine of the aircraft, feel the effect of aerodynamic forces on the controls or air turbulence on the airframe, or see from the point of view of the aircraft without the presence of compensatory artificial sensors and displays. Compared to a pilot onboard the aircraft, the unmanned aircraft pilot receives much less directly sensed information during a flight.

Recent research has suggested the importance of having multiple types of sensory information in the cockpit. There is a phenomenon called *multi-modal reinforcement,* in which the simultaneous presentation of a visual and auditory input reinforces the perception of both. For example, people have more trouble perceiving a flickering point of light as the intensity of the light is decreased. However, if the light is accompanied by a sound, the ability to perceive the light improves (Kayser, 2007). In addition, brain imaging studies have shown that certain regions of the brain are used specifically for the integration of multiple sensory inputs and that many activities, such as the localization of a sound in space, rely on multi-sensory inputs (Kayser, Petkov, Augath, & Logothetis; 2005).

For manned aircraft, the presence of multi-sensory inputs is a given. Pilots of manned aircraft might not even be aware of the availability of several different types of sensory inputs occurring at the same time. However, it is likely that each type of input has a reinforcing effect on the others that allows for a rapid diagnosis and response of both normal and unusual events in the cockpit.

The situation for the pilot of a UAS is much different. UAS pilots receive information regarding the state and health of their aircraft solely through electronic displays.[1] The purpose of this paper is to document the types of sensory information that are not available to the UAS pilot, compared to the onboard pilot, and to discuss how differences might affect the operation and safety of flight of UASs. In addition, the paper will look for evidence of the degree to which the lack of multiple sensory modes has led to UAS accidents and how the design of various systems attempts to overcome mode deficiencies. We will look at research that has proposed various ways to augment sensory information for UAS pilots and current federal regulations that address sensory information in manned aircraft. The final section of the paper will include recommendations for system design for UAS control stations and training that will help to address problems related to the lack of multiple modes of sensory information.

Background on Human Sensory Capabilities

Before we can fully appreciate the types of sensory information that are available to the UAS pilot, we must develop an understanding of basic human sensory capabilities. In this section, we will review the types of sensory information that are available to the pilot during flight in manned aircraft. For each type of sensory information, it will be noted how the information is used to maintain safe flight.

Visual Information

By far, the most important and most used sense for the pilot is vision. Even when flying in instrument meteorological conditions, the pilot relies on visual information from the displays to determine the position and attitude of the aircraft. When flying in visual meteorological conditions, not only does the pilot rely on information from the displays, but there is also a wealth of visual

[1]Note that this analysis excludes UASs that are controlled through visual line of sight.

information available by looking outside the aircraft. Visual information can be separated into four categories: foveal vision, visual accommodation, color vision, and peripheral vision. Each of these categories is distinguished by the type of information it provides.

Foveal Vision

Foveal vision provides information to the pilot in the form of symbols and images that can be brought into focus within the visual field of view. It depends on the ability to resolve detail within the visual field of view. This ability is generally referred to as visual acuity. The resolution of detail primarily involves a very small portion of the eye called the fovea, which corresponds to only about 1 degree of the visual field of view (Antuñano, 2002).

One obvious question that arises with a discussion of visual acuity is how far away an object can be and still be seen by an observer. The most common answer to this question uses the angular size of an object in relation to the total visual angle impinging on the eye at any given moment. When expressed in terms of angular size, the most commonly accepted resolving ability of humans is 1 min of visual arc (1/60th of a degree) (O'Hare & Roscoe, 1990). The formula for computing angular size is: tan θ = height (or more precisely the visual cross-section of the object) divided by distance (of the object from the observer). For example, an object that has a visual cross-section of 1 ft and is 3,438 ft from an observer subtends 1 min of visual arc (tan θ = 1/3438 = .00029; taking the inverse tangent of .00029 yields .016666, which is equal to 1/60 of a degree, or 1 min of arc). In more direct terms, an object that has a 1 ft visual cross-section can theoretically be recognized from as far away as 3,438 ft. The visual cross-section of an object is determined more by the shape of the object than the size of the object. An aircraft with a wingspan of 20 ft, for example, does not present that much area to an observer if looked at edge-on.

There is a direct linear relationship between the visual cross-section of the object and the visual recognition distance. Doubling the visual cross-section of the object will double the distance at which it can be seen. Halving the visual cross-section will halve the distance, and so on.

Of course, there are several other factors that influence the visibility of objects. For example, the brightness of an object and the amount of contrast an object has against its surroundings both affect object visibility and, therefore, object recognizability. In addition, visual acuity drops rapidly as an object falls outside the 1-degree area of foveal vision. Harris (1973), for example, demonstrated that the probability of detecting a DC-3 aircraft at a range of 5 mi was 100% when looked at directly, but the probability dropped to less than 20% when the image was displaced 10 degrees from the center. Visual acuity can also be affected by physiological factors. Alcohol and tobacco use, low blood sugar, and sleep deprivation can impair vision. In addition, inflight exposure to low barometric pressure without the use of supplemental oxygen (above 10,000 ft during the day and above 5,000 ft at night) can result in hypoxia (low blood oxygen levels), which can also impair vision (Antuñano, 2002).

For these and other reasons, the National Transportation Safety Board (NTSB) has stated that an aircraft must subtend at least 12 min of visual arc before there is a reasonable chance of seeing it (e.g., NTSB, 1987). Furthermore, a report by the Australian Bureau of Air Safety Investigation states that in sub-optimal visual conditions (i.e., low-light, low-contrast), a figure of 24 to 36 min of arc is more realistic (BASI, 1991). Using the NTSB value of 12 min of visual arc, an object that spans 1 ft of visual width could be seen only if it were as close as 286 ft. In sub-optimal conditions (requiring 36 min of visual arc), this same object would only be seen if it were within 95 ft of the viewer.

In terms of the type of information that foveal vision provides to the pilot, very precise quantitative data can be gained in a very brief period of time. Exact information regarding the speed, attitude, heading, and other flight parameters of the aircraft is available through the cockpit displays and can be processed rapidly. Also, the information can be continuous in nature (as opposed to categorical information that can have one of only a few different values). On the other hand, accessing this information requires that the pilot focus attention directly at a specific location, to the exclusion of other visual information. This is one reason pilots are taught the importance of instrument scanning techniques so that information that is available only visually is updated regularly.

Visual Accommodation

It is interesting to note that, while foveal vision is normally measured at a distance of 20 ft, using a Snellen exam eye chart, foveal vision requirements rarely occur at that distance. Most flight-related visual activities require looking at displays or other objects within the cockpit that are approximately 2 to 4 ft from the observer. Objects of interest located outside the cockpit are most often hundreds or even thousands of feet away from the observer. The ability to shift the focus of the eye to various distances is called accommodation. Accommodation is affected by age and fatigue, as well as other factors. The BASI report (1991) suggests that the average pilot probably takes several seconds to accommodate to a distant object.

The type of information that is available to the pilot through visual accommodation consists primarily of distance data, but only for relatively short distances (approximately 30 ft or less). Accessing this data can be rather slow, and the act of visual accommodation can make it more difficult to access foveal vision information that might be available.

Color Vision

According to O'Hare and Roscoe (1990), humans are capable of distinguishing approximately 130 different colors across the range of visible light. However, this number is dependent on both biological and cultural factors. In addition, the use of colors to convey information in displays should be far more limited. Most human factors guidelines suggest using no more than 7 colors for conveying information (e.g., FAA, 2003).

There are several types of deficiencies related to the sensing of specific ranges of colors. The use of colors in displays to present specific information can limit some people from perceiving that information. It is important that designers of displays are aware of which types of color sensing deficiencies might preclude full use of a display.

There are 2 major types of color deficiencies. The most common is red-green deficiency, meaning difficulty in distinguishing red and green hues. This deficiency is present in approximately 8-10% of the male population. Blue-yellow deficiency affects another 1-2% of the male population. Less than 1% of females have any type of color sensing deficiency (Hoffman, 1999).

Information available through color sensing is rapidly accessible but limited to categorical values. Attention must be directed toward the information but not as precisely as is required for foveal vision information. This widened field of view is sometimes referred to as parafoveal vision because the information can be processed outside the central 1-degree field of view but does not include the entire visual field of view. Estimates vary, but parafoveal vision includes approximately the central 10-degree visual field (Gilbert, 1950).

Peripheral Vision

While the majority of visual information is processed within the central 1-degree vertical and horizontal visual field, the entire visual field of the eyes is normally about 200 degrees on the horizontal plane and 135 degrees on the vertical plane. The non-central field of view is referred to as peripheral vision (except, as noted above, when a portion of it is referred to as parafoveal vision). Most of the information that is conveyed through peripheral vision is about movement. This includes both movement of objects within the field of view and movement of the individual through space. This information is not very precise but serves more to attract the attention of the viewer to a location. Within a cockpit environment, a changing visual stimulus such as a blinking light within the peripheral visual field can serve as a means to attract attention.

Auditory Information

Sound can be described in terms of three variables: frequency (or pitch); intensity (or loudness); and duration. Sound frequencies that are audible to humans fall in the range of 20 to 20,000 cycles per second or hertz (Hz), with the greatest sensitivity occurring in the region of 1-3 KHz (O'Hare & Roscoe, 1990). The region between 1-3 KHz is also where human conversation normally occurs. Sound intensity is described in decibels (dB). A decibel is basically a measure of the pressure level that a sound exerts on the ear. For reference, a whisper has a decibel level between 20 and 30. The cabin of a jet airplane has a sound intensity between 60 and 88 dB. The cockpit of a small propeller-driven aircraft has a sound intensity between 70 and 90 dB. Standing close to a jet engine exposes one to a sound intensity between 130 and 160 dB (Antuñano & Spanyers, 1998).

Within the manned aircraft environment, sound is produced from a variety of sources. Sounds are produced by aircraft equipment, such as powerplants, transmission systems, jet efflux, propellers, rotors, hydraulic and electrical actuators, cabin conditioning and pressurization systems, cockpit advisory and alerting systems, and communications equipment. Sound is also produced by the aerodynamic interaction between ambient air and the surface of the aircraft fuselage, wing control surfaces, and landing gear. Pilots, with some experience, learn to distinguish the variety of sounds that their aircraft makes under normal operations, such as the positioning of the landing gear and flaps. A change in these sounds is a useful clue to the pilot that a malfunction or some other anomalous condition has occurred (Antuñano & Spanyers, 1998).

Information available aurally can be as precise as foveal vision information, but the speed of transmission is much slower. For example, altitude information can be transmitted aurally by having a voice announce the altitude, but the update rate of that information would be much slower than a visual display. On the other hand, aural information does not require that the head be oriented in a particular direction.

Spatial Orientation/Vestibular Information

Spatial orientation refers to our ability to recognize and maintain our body position relative to the environment. While the visual system plays a key role in spatial orientation, a second important source of information comes from the vestibular system. Vestibular information is derived from organs within the inner ear, the semicircular canals, and the otolith organ. Movement of the body through space is sensed through the vestibular system so as to allow spatial orientation to be maintained. As with aural information, vestibular information does not require that the pilot's attention be directed in a particular direction.

Proprioceptive and Kinesthetic Information

Proprioception is the sensing of changes in the muscles and tendons of the body. Kinesthetic information is information regarding body movement, as perceived by the muscles, tendons, and joints of the body. In the cockpit, most proprioceptive and kinesthetic information is received as a result of movement of the controls (primarily the yoke and rudder pedals) but can also be derived from the sensing of gravitational and accelerational forces on the body as the aircraft moves through the air.

While the pilot needs to be holding the controls to receive proprioceptive information from them, attention does not need to be directed at the controls. A change in the expected feel of the controls is sufficient to direct attention to the proprioceptive information.

Haptic Information

Haptic information refers to the sense of touch. Interface designers make use of haptic information in a variety of ways. One example is found on most computer keyboards, where there is a raised ridge on the "F" and "J" keys on the keyboard to cue users where to place their fingers without having to look at the keyboard. Designers of cockpit controls make use of haptic information to assist the pilot in distinguishing certain controls from others. For example, the shapes and textures of gear and flap levers are used to assist the pilot in distinguishing these controls from others located nearby. Haptic information also includes vibration, either caused by a system anomaly or purposely generated as an alerting device.

Similar to proprioceptive information, attention does not need to be directed toward the source of the haptic information to be processed (Ho, Tan, & Spence, 2006). However, it is expected that the haptic information must be sufficiently different from what is expected for it to capture attention, although no specific research on this issue could be found.

Sense of Smell

While not usually thought of as critical, the sense of smell can nevertheless provide important information to the pilot. Boser (2002) reported that the first indication of trouble for a number of in-flight fires was the sight or smell of smoke. For example, in the case of SwissAir Flight 111 that suffered an in-flight fire and crashed on September 2, 1998, the crew smelled smoke in the cockpit a full 3 min prior to seeing smoke.

Negative Aspects of Sensory Information in Manned Aircraft

Though sensory information is necessary for the performance and safety of a flight, there are negative aspects to sensory information that should not be overlooked. In an analysis of sensory information for unmanned aircraft, it is important to note that the absence of certain sensory stimuli might actually have a positive effect regarding the safety of the flight and the health of the pilot. This section will review negative aspects of several modes of sensory information and will discuss how they apply to the piloting of unmanned aircraft.

Visual Accommodation

In regard to visual accommodation, two phenomena -- empty field myopia and focal traps -- can interfere with the ability to accommodate to an object. Empty field myopia occurs when there is an absence of visual cues available, such as when looking into a clear blue or overcast gray sky. In such cases, the normal response of the eyes is to accommodate to what is called the "resting state" or "dark focus" position. This position is typically around 56 cm (approximately 22 in) (Roscoe & Hull, 1982). However, the dark focus position of the eye increases with age, reaching optical infinity around age 50 (O'Hare & Roscoe, 1990).

Empty field myopia can be a problem for manned aircraft pilots when trying to scan for traffic. It can also be a problem for UAS pilots who control their aircraft through visual line of sight. In addition, it can be a problem for visual observers that are needed to separate the UAS from other aircraft in the area. Interestingly, because dark focus position increases with age, it suggests older people will be less affected by empty field myopia than younger people. However, other age-related vision deficits most likely offset this advantage. UAS pilots that do not control through visual line of sight will not be affected with issues related to visual accommodation.

A focal trap, also known as the Mandelbaum effect, occurs when an object located close to the dark focus position of the eye causes the eye to involuntarily focus

at that position, making it difficult to see more distant objects. Window posts and dirty windscreens are particularly likely to produce the Mandelbaum effect, thus interfering with the task of scanning for traffic (BASI, 1991). As with empty field myopia, UAS pilots that require visual line of sight would be affected by focal traps, but those that do not require visual line of sight would not be affected.

Visual Illusions

While vision is essential to the safe and effective operation of an aircraft, there are times when the visual information that is received by pilots of manned aircraft can be misinterpreted. Several potential visual illusions have been identified that could misdirect the pilot during a flight (FAA, 2000a). For example, an illusion can be experienced during landing when the shape and/or slope of a runway is not in agreement with pilot expectations. Through experience, pilots develop an expected image of the shape of a runway and use this image to judge the appropriate approach angle (Mertens, 1979). When approaching an upsloping runway, pilots can misinterpret the runway image as an indication that their approach is too high. This would be especially problematic at night, where a lack of other visual references might lead them to descend too soon, resulting in an accident (FAA, 2000a).

A second type of visual illusion occurs when the pilot receives false visual references during a flight. These illusions can be caused by flying over a banked cloud, night flying over featureless terrain with ground lights that are indistinguishable from a dark sky with stars, or night flying over a featureless terrain with a clearly defined pattern of ground lights and a dark, starless sky (FAA, 2000a). For example, under appropriate lighting conditions, a long, straight road in a desert when approached from the side might appear as a horizon line to a pilot, thus giving the illusion that the horizon was lower than was the actual case, which could lead to impacting the terrain inadvertently.

In general, UAS pilots that rely on an out-the-window view to pilot their aircraft could still be affected by the visual illusions described above. However, because the out-the-window view is displayed electronically, it might be possible to add information to the scene that would prevent these illusions from occurring. Research looking at enhancing the electronic out-the-window display is discussed in a later section of this paper. In addition, a large number of UASs do not rely on an out-the-window display for pilot control of the aircraft, so pilots of these systems would not be impacted by such illusions.

Auditory Information

Exposure to high levels of sound for long periods of time can result in hearing loss. The federal government has established exposure limits for various sound levels in the workplace. These Occupational Safety and Health Administration (OSHA) limits vary from 8 hrs per day for 90 dB to as little as 15 min per day for 115 dB (Antuñano & Spanyers, 1998). Research at the FAA Civil Aerospace Medical Institute examined how noise exposure from aircraft engines can affect pilots' hearing (Beringer & Harris, 2005), showing that pilots suffered more significant hearing loss relative to non-pilots. Importantly, the hearing loss was most severe for sounds in the 1-3 Khz range, which is the range of sound for the human voice. The findings are important in regard to the development of alerts and alarms in the cockpit and in the ability of older pilots to recognize and respond to voice communications.

The types and levels of sound vary greatly for pilots of UASs. However, in general, UAS pilots are not exposed to the same level of noise as manned aircraft pilots because they do not have to be in close proximity to the aircraft engines, which are usually the loudest source of noise for pilots.

Spatial Orientation/Vestibular Information

Ordinarily, the vestibular system performs exceptionally well in helping to maintain spatial orientation. However, the information received by the vestibular system can sometimes cause confusion and disorientation. A recent FAA publication states that 5 -10% of general aviation accidents can be attributed to spatial disorientation and that 90% of those accidents are fatal (Antuñano, 2003).

The cause of vestibular illusions for pilots of manned aircraft is a discrepancy between the movement and position of the aircraft indicated by what the vestibular system is experiencing and the actual movement and position of the aircraft. These illusions are most dangerous when there are no reliable external visual references available to the pilot that could provide a separate source of information regarding the movement and position of the aircraft, such as when flying in instrument meteorological conditions. The following vestibular illusions primarily involve the semicircular canals:

- The Leans – This illusion is caused by a gradual and prolonged turn that is not noticed by the pilot because it is below the rotational acceleration (of about 2 degrees per sec) required for detection by the semicircular canals. The illusion occurs after the wings are leveled; the pilot then experiences the feeling that the aircraft is banking in

the opposite direction. The pilot's normal reaction to this experience is to lean in the direction of the original turn.
- The Graveyard Spin and Graveyard Spiral – Both the Graveyard Spin and Graveyard Spiral are caused when the sensation caused by a spin or turn progressively decreases until it cannot be felt. At this point, if the turn or spin is halted, the pilot will feel that the aircraft is turning in the opposite direction.
- The Coriolis Illusion – This illusion is caused by the simultaneous stimulation of 2 semicircular canals, usually by tilting the head forward or backward while the aircraft is turning. This leads to a perceived climb, pitch, or roll disorientation for the pilot and the potential to lose control of the aircraft. Improper placement of navigation displays could result in a situation where the pilot is required to tilt his/her head forward during a turning maneuver (Williams, 1999).

Vestibular illusions involving primarily the otolith organs are as follows:
- The Inversion Illusion – This illusion involves a steep ascent in a high-performance aircraft, followed by a sudden return to level flight. This causes an illusion that the aircraft is in inverted flight.
- The Head-Up and Head-Down Illusion – The Head-Up and Head-Down illusions involve a linear acceleration or deceleration during level flight. The acceleration results in the perception that the nose of the aircraft is pitching up. A linear deceleration results in the perception that the nose of the aircraft is pitching down.

In general, UAS pilots will not be subjected to movement that could lead to any of the vestibular illusions described above. However, there might be occasions where a pilot is moving while controlling the UAS. Self, Ercoline, Olson, and Tvaryanas (2006) have predicted that piloting a manually controlled UA from a moving platform will be spatially disorienting. In addition, an analysis of accident data has shown that 10% of UA accidents were in part due to the misperception of the location and attitude of the aircraft (Tvaryanas, Thompson, & Constable, 2005). One explanation of the cause of this misperception is a mismatch between visual and vestibular or proprioceptive stimuli (Reed, 1977).

Advantages and Disadvantages of Sensory Modes

Given the preceding analysis, several conclusions can be drawn regarding the advantages and disadvantages of the various sensory modes in manned aircraft. Foveal vision is by far the most efficient way of receiving large amounts of information very quickly. In addition, independent pieces of information can be displayed visually at the same time without interfering with each other (e.g., altitude, airspeed, and heading can all be displayed simultaneously on different portions of the display area). The primary disadvantage of foveal vision is that the eyes must be focused on a particular location for the information from that location to be processed.

Visual accommodation, color vision, and peripheral vision have limited bandwith capabilities. Color vision can be useful as a means to provide additional or redundant coding to the pilot, but care must be taken to ensure that pilots with color deficiencies do not have problems with the processing of that information if critical flight information is coded only by color.

In contrast with visual information, auditory information can come from any direction relative to the observer and still be heard and processed. On the other hand, separate simultaneous auditory signals will interfere with each other. This fact, along with the fact that auditory information does not have the same bandwidth capacity as visual information, means that auditory displays could not be used as the sole method for monitoring and controlling aircraft position and status.

Vestibular, proprioceptive, and haptic information do not have the bandwidth or precision of visual or auditory information, although haptic coding schemes have been developed for language communication (e.g., Geldard, 1957). Vestibular information also has the disadvantage of providing misleading information to the pilot under certain circumstances. However, these information modes have the advantage of not requiring the pilot to focus attention on a particular location.

Pilot Sensory Information for Anomalous Events

The prevalence and importance of sensory information for pilots can be illustrated by looking at how sensory information contributes to the recognition and diagnosis of various anomalous events. This section will look at 6 anomalous events to demonstrate the range of sensory modes available to the pilot during those events. Information regarding these events comes primarily from advisory circulars or other FAA documents that address particular anomalous events but also includes information collected from pilots and other aviation experts.

Loss of Engine

At first blush, it would seem that the loss of an engine, especially in a single-engine aircraft, would be more than obvious to the pilot in terms of a dramatic change in sound. Pilots flying most single-engine propeller aircraft

can also see the propeller. However, engines can fail without seizing up altogether. In addition, for pilots of multi-engine aircraft, the recognition of engine loss can be more difficult. The symptoms of an engine problem vary according to the type of engine, the number of engines, and their placement on the aircraft. As an example of the variety of ways aircraft engines can fail and the sensory indications of those failures, Table 1 (below) is taken from an FAA report entitled "Turbofan Engine Malfunction Recognition and Response Final Report" (FAA, 2000b). Table 1 represents only a portion of the table appearing in the report. It lists the first 7 of 24 different types of engine malfunctions that were identified. These 7 malfunctions were associated with 54 of 79 accidents or incidents associated with a turbofan engine malfunction. It is reproduced in part here to illustrate several important points.

First, there are many ways an engine can fail, and they all have somewhat different symptoms. However, most of the failures are accompanied by a distinct sound, described in the table as a "bang." In addition to this sound, many of the failures are accompanied by a vibration of the aircraft (haptic information), aircraft yaw for aircraft with multiple engines (vestibular information), aircraft

Table 1. Types and symptoms of a variety of turbofan engine malfunctions.

	PROBLEM FLIGHT PHASE	SYMPTOM	TRAINING ACTION
SURGE	***TAKEOFF > V1***	LOUD BANG. (repetitive) N1/N2 Drop, EGT Increase, AIRCRAFT VIBRATION, P0SSIBLE YAW	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1, N2, & EPR DECREASING, EGT INCREASING, TRAIN TO KEEP CONTROL OF THE AIRCRAFT, CONTINUE TAKEOFF, CLIMB TO A SAFE ALTITUE THEN THROTTLE BACK TO CLEAR SURGES AND REAPPLY POWER AND TROUBLESHOOT PER CHECKLISTS
SURGE	***TAKEOFF < V1***	LOUD BANG (usually 1 or 2). N1/N2 drop, EGT increase, AIRCRAFT VIBRATION, YAW	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1 & N2 & EPR DECREASE WHILE EGT INCREASES, TRAIN TO REJECT THE TAKEOFF
SURGE	***TAKEOFF > V1***	LOUD BANG (usually 1 or 2). N1/N2 drop, EGT increase, AIRCRAFT VIBRATION, YAW	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1 & N2 & EPR DECREASE WHILE EGT INCREASES, TRAIN KEEP CONTROL OF THE AIRCRAFT AND CLIMB TO A SAFE ALTITUDE BEFORE ATTEMPTING TO TROUBLESHOOT.
SURGE	***INITIAL CLIMB***	LOUD BANG (usually 1 or 2). N1/N2 drop, EGT increase, AIRCRAFT VIBRATION, YAW	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1 & N2 & EPR DECREASE WHILE EGT INCREASES, TRAIN KEEP CONTROL OF THE AIRCRAFT AND CLIMB TO A SAFE ALTITUDE BEFORE ATTEMPTING TO TROUBLESHOOT
SURGE	***CRUISE***	Quiet bang (possibly repetitive PARAMETER FLUCTUATION (may be only momentary), AIRCRAFT VIBRATION,	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1 & N2 & EPR DECREASE WHILE EGT INCREASES, TRAIN TO KEEP CONTROL OF THE AIRCRAFT AND CLIMB TO A SAFE ALTITUDE BEFORE ATTEMPTING TO TROUBLESHOOT
POWER LOSS single engine	***INITIAL CLIMB***	Bang or fire warning or very severe vibration, aircraft yaw, high EGT	SIMULATE LOUD NOISE, SUDDEN AIRCRAFT SHUDDER, FLUCTUATION OF ENGINE PARAMETERS N1 & N2 & EPR DECREASE WHILE EGT INCREASES, TRAIN TO KEEP CONTROL OF THE AIRCRAFT AND CLIMB TO A SAFE ALTITUDE BEFORE ATTEMPTING TO TROUBLESHOOT
POWER LOSS single engine	***APPROACH /LANDING***	Parameter spool down. Services (generators) drop off line	SIMULATE AIRCRAFT REACTION TO AND FLIGHT DECK PANEL CHANGES FOR LOSS OF SINGLE ENGINE. TRAIN RECOGNIZE THE SITUATION AND TO MAINTAIN AIRCRAFT CONTROL DURING LANDING OR GO-AROUND

engine display indications, and changes in the feel and movement of the controls (proprioceptive information). While this table was created specifically for turbofan engine malfunctions, the general sensory indications are similar across a wide variety of engine types.

Icing

FAA Advisory Circular 91-74, Pilot Guide to Flight in Icing Conditions (AC-91-74), provides information regarding the recognition of icing conditions in manned aircraft. Indications of icing are as follows:

- Loss of power – More power is required to maintain airspeed. Loss of power is noticeable through a change in the sound of the engine and through engine power displays.
- Visible accumulation of ice on surfaces of the aircraft. Some portions of the aircraft are more visible to the pilot than others. Specific parts such as windshield wipers, pod pylons, or landing lights will be more noticeable to the pilot.
- Controls become more difficult to move for those aircraft with mechanical linkages between the controls and the aircraft surfaces (proprioceptive information).
- Some aircraft are equipped with sensors that can detect icing conditions. These sensors can then trigger an auditory and/or visual warning display for the pilot.

Stall

FAA Advisory Circular 61-67B, "Stall and Spin Awareness Training," provides the following description of the sensory indications associated with a stall:

> One indication of a stall is a mushy feeling in the controls and less control effect as the aircraft's speed is reduced. This reduction in control effectiveness is attributed in part to reduced airflow over the flight control surfaces. In fixed-pitch propeller airplanes, a loss of revolutions per minute (RPM) may be evident when approaching a stall in power-on conditions. For both airplanes and gliders, a reduction in the sound of air flowing along the fuselage is usually evident. Just before the stall occurs, buffeting, uncontrollable pitching, or vibrations may begin. Many aircraft are equipped with stall warning devices that will alert the pilot when the airflow over the wing(s) approaches a point that will not allow lift to be sustained. Finally, kinesthesia (the sensing of changes in direction or speed of motion), when properly learned and developed, will warn the pilot of a decrease in speed or the beginning of a "mushing" of the aircraft. These preliminary indications serve as a warning to the pilot to increase airspeed by adding power, and/or lowering the nose, and/or decreasing the angle of bank (p. 3).

From this paragraph, it is clear that the sensory information related to stall recognition includes haptic, proprioceptive and kinesthetic cues, auditory cues, both from auditory displays and from ambient airflow sounds, vestibular cues, and visual cues from engine displays and perhaps visual out-the-window cues related to changes in velocity or pitch.

Turbulence

FAA Advisory Circular 120-88A (FAA, 2006) describes turbulence in terms of both duration and intensity. Turbulence duration is described as occasional, intermittent, or continuous. Turbulence intensity is described on a 6-point scale of light chop, light turbulence, moderate chop, moderate turbulence, severe, and extreme. The first 4 levels of intensity are usually dangerous only to passenger and crew within the aircraft, not to the aircraft itself. Severe turbulence can cause the momentary loss of control of the aircraft, and extreme turbulence can result in damage to the structure of the aircraft. Indications of turbulence, of course, are primarily vestibular, haptic, kinesthetic, and proprioceptive in nature. However, sudden movements of the aircraft can also be noticed visually as well.

Unusual Attitude

Earlier we discussed the many types of vestibular illusions that can be experienced in an aircraft. In the case of unusual attitudes, sensory information such as vestibular information and certain types of visual information can contribute to or exacerbate the problem of flight in unusual attitudes. When flying in clouds, out-the-window visual information can give the false impression of changes in attitude of the aircraft or can mask changes in attitude. False vestibular information can contribute to those impressions. The only accurate sensory information available to the pilot under these conditions is through the primary flight displays.

Loss of Onboard Electrical System

The indications for the loss of the onboard electrical system would be primarily visual, although some aircraft are equipped with an auditory alarm. No other sensory modes would provide useful information to the pilot for this anomaly.

UAS Sensory Information for Anomalous Events

Unlike manned aircraft, UASs can only provide sensory information to the pilot through the control station controls and displays. While these controls and displays can theoretically act through any of the sensory modalities discussed in this paper, they most commonly

are visual and auditory in nature. Because most current UASs restrict the number of sensory modalities available to the pilot relative to manned aircraft, it is important to understand the effect this might have on the UAS pilot. For comparison with anomalous events in manned aircraft, a questionnaire was sent to several manufacturers soliciting responses in regard to specific systems. The questionnaire asked pilots or others familiar with a particular UAS what types of sensory information were available to pilots during specific anomalous events. Respondents were asked what display indications were available to pilots under these conditions and what kind of training was given to pilots for the recognition of these events. A listing of responses to this questionnaire is provided in Appendix A.

Loss of Data Link

This anomalous event is associated only with unmanned aircraft. However, because it is extremely critical to UAS safety, an analysis of the types of sensory information available to UAS pilots is warranted. All UASs have visual display indications of a loss of data link. In addition, some also have an auditory warning. For the visual displays, there is usually an indication of strength of the data link connection, either in the form of a signal strength meter for analog signals or a packet counter for digital signals. There is also a display indication when the data link signal falls below a predetermined criterion for a certain length of time. This indication is usually a text warning that is sometimes accompanied by a change in color of the display or other visual indication. As an example, Figure 1 shows the display for the SkyEye UAS. Data link information is presented using a light that is colored red or green (separately for the uplink and downlink) in the upper left corner of the display and a signal strength indicator directly below these lights. It is interesting to note that these status lights are either green or red, recalling that green-red color deficiency is the most commonly found in the general population.

Loss of Engine

UASs with an out-the-window camera view for the pilot have an external visual indication of certain anomalous events like a loss of engine, though the indication is indirect, such as the nose of the aircraft dipping momentarily. UASs also have engine display indications available. Because the displays for UASs are electronic, it is quite common in many of these systems that the displays themselves will change color, in addition to having a warning appear separately. For example, in the Hunter control station, the RPM values will change color if they fall outside preset boundary levels. This provides a separate source of information to the pilot, in addition to whatever warning messages might be available. What this method does not provide is an indication to the pilot that the RPM is

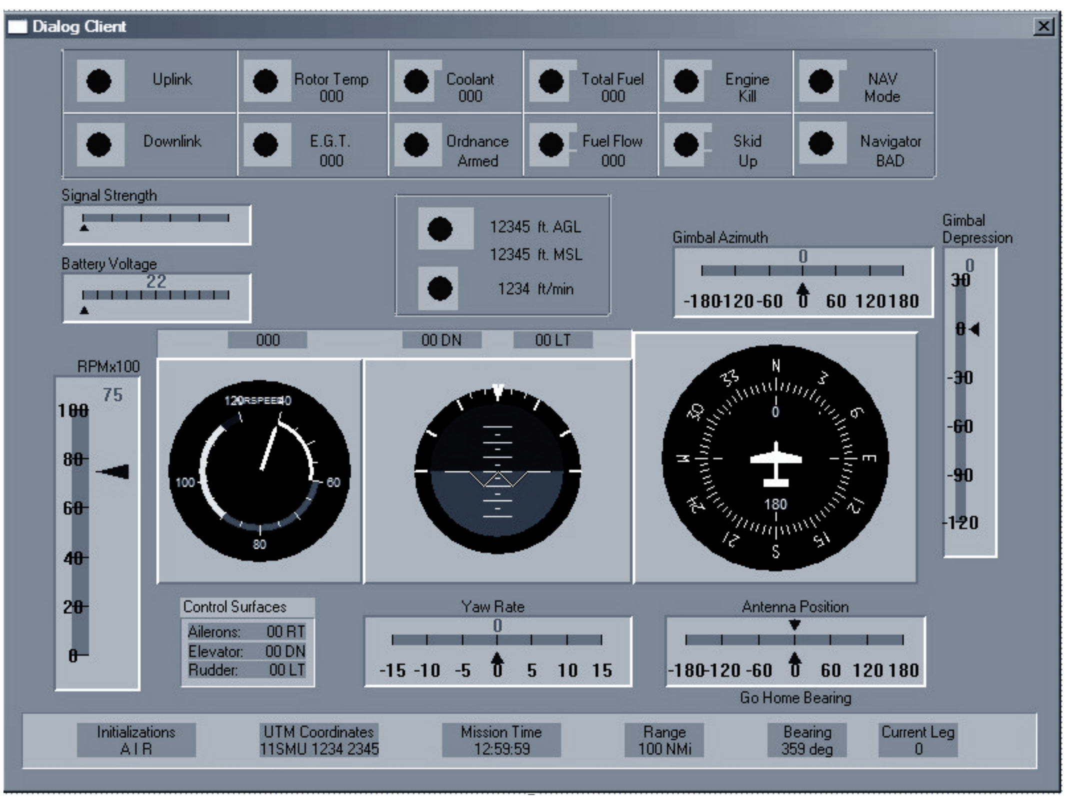

Figure 1. SkyEye pilot display.

approaching a certain boundary level, as is available in traditional aircraft displays through the use of colored arcs located on the outside of the RPM indicator.

Additionally, some UASs have an auditory alarm for loss of an engine. However, the alarm is sometimes a general warning and does not provide a direct indication of the problem. For example, the crash of a Predator B UAS in April 2006 included an auditory alarm. But as the accident report indicates, the alarm did not indicate the exact nature of the problem. The accident report describes it this way:

> There is an audible warning when an engine failure occurs. However, the same tone is used for every warning; the sound was not distinctive for a loss of engine power. The avionics technician stated that he heard the warning, but thought it was activating because they lost the Iridium satellite. In addition to the aural warning, the pilot should have seen a loss of torque and an exhaust gas temperature warning on the heads-down display (NTSB Accident Rpt# CHI06MA121, p.5).

Icing

In UASs, icing is indicated indirectly through the visual displays, specifically through an engine power display. Also, if the aircraft has a camera that can be pointed at the aircraft surfaces, it might be possible to detect ice in that manner. In addition, ice might be noticeable on the camera lens itself. However, it should be noted that payload cameras are not well-suited for the detection of icing because they are not usually operated by the pilot and are dedicated to a task other than controlling of the aircraft and monitoring of aircraft status.

Stall

Indications of stall in a UAS are extremely limited and consist of nothing more than visual display indications related to aircraft airspeed and power. The automated nature of most UAS would prevent most instances of stalls. However, certain types of failures might force the aircraft to stall despite the presence of automation.

Turbulence

UAS indications of turbulence are generally limited to visual displays or an out-the-window camera view. However, some systems have been equipped with a display that indicates turbulent conditions.

Unusual Attitudes

Unusual attitudes in UASs have the benefit that the pilot would not be subjected to misleading vestibular cues. However, it is not clear how quickly a UAS pilot might notice that the aircraft was changing attitude without the presence of vestibular and proprioceptive cues to alert that an anomalous event was occurring.

Comparing Sensory Information for Anomalous and Normal Events

A summary of the comparison of sensory information available to manned and unmanned aircraft pilots is shown in the following tables. For UASs, manufacturers have the option of providing sensory information that simulates what the pilot onboard the aircraft receives. For example, some systems provide a nose camera view that simulates what a pilot looking out of the cockpit would see. However, this electronic simulation of an out-the-window view would not exactly match the view that the onboard pilot would see. Manufacturers can also simulate vestibular, auditory, proprioceptive, and haptic information as well. But note that “simulation” in this context is not merely providing that mode of sensory information to the pilot. Instead, “simulation” refers to the attempt to replicate the sensory information available to the onboard pilot.

Table 2. Comparing sensory information for loss of engine.

Sensory Information	Manned	Unmanned
Engine noise	Yes	No
Engine displays	Yes	Yes
Auditory warning	Yes	Yes
Aircraft yaw (for multiengine aircraft)	Yes	No
Aircraft vibration	Yes	No
Change in feel of control forces	Yes	No

Table 3. Comparing sensory information for aircraft icing.

Sensory Information	Manned	Unmanned
Engine sound change	Yes	No
Change in sound of airflow over wings and fuselage	Yes	No
Engine displays	Yes	Yes
Visible accumulation of ice on aircraft	Yes	No
Aircraft vibration	Yes	No
Change in feel of control forces	Yes	No

Table 4. Comparing sensory information for aircraft stall.

Sensory Information	Manned	Unmanned
"Mushy" feeling in the controls (proprioceptive information)	Yes	No
Display of airspeed and engine power	Yes	Yes
Change in sound of air flow on fuselage	Yes	No
Aircraft vibration (haptic information)	Yes	No
Auditory stall warning	Yes	Yes
Change in direction or speed of motion (kinesthetic and vestibular information)	Yes	No

Table 5. Comparing sensory information for turbulence.

Sensory Information	Manned	Unmanned
Rapid change in altitude or heading (vestibular, kinesthetic information)	Yes	No
Flight displays (altitude, airspeed, attitude)	Yes	Yes
Change in feel of control forces	Yes	No
Visual out-the-window indications	Yes	No
Turbulence warning display	No	Yes

Table 6. Comparing sensory information for unusual attitudes.

Sensory Information	Manned	Unmanned
Vestibular and kinesthetic sensations from changes in aircraft attitude and speed	Yes	No
Aircraft displays of attitude, airspeed, and altitude	Yes	Yes
Visual out-the-window indications	Yes	No
Change in feel of control forces	Yes	No

Table 7. Comparing sensory information for change in flap setting.

Sensory Information	Manned	Unmanned
Sound of flap movement	Yes	No
Aircraft display of flap setting and airspeed	Yes	Yes
Change in speed of aircraft (kinesthetic information	Yes	No
Visual out-the-window indications of change in speed	Yes	No

Table 8. Comparing sensory information for change in power setting.

Sensory Information	Manned	Unmanned
Change in sound of engine	Yes	No
Aircraft display of power setting, airspeed and attitude	Yes	Yes
Change in speed of aircraft (kinesthetic information	Yes	No
Visual out-the-window indications of change in speed	Yes	No

Note that visible accumulation of ice on the aircraft could be seen by an onboard camera that was capable of looking at the aircraft wings and fuselage. In fact, ice accumulation could also occur on the camera lens itself, which would be visible to the camera operator. However, not all unmanned aircraft have onboard cameras, and the purpose of the camera is not to detect icing conditions on the aircraft. Thus, the expectation of the effectiveness of an onboard camera to detect icing accumulation is low.

Again, as with the icing example, an onboard camera could provide visual indications of turbulent conditions, but only if the camera display were interpreted correctly. Without the presence of the other sensory cues, the shaking of the camera could be misinterpreted as a distortion of the camera signal or perhaps as the shaking of the camera independently of the aircraft (because the camera had come loose from its housing perhaps).

In addition to anomalous events, there is also a difference in sensory information associated with normal flight events. Tables 7 and 8 compare the sensory information available to the pilot of manned and unmanned aircraft for normal flight events.

As seen in these tables, the number of types of sensory information available to manned aircraft pilots is always greater than for unmanned aircraft pilots. For some types of events, there are 4 or 5 more varieties of information available for the detection and identification of the event for the pilots of manned aircraft. More importantly, the types of information that are lacking in UASs are those that do not require the specific attention of the pilot to receive that information. The pilot of a UAS is limited almost entirely to visual information from the control station displays, which requires that the pilot be looking at the proper location (although some systems do have auditory displays).

In the case of anomalous events, multi-sensory inputs can serve to alert the pilot that an event is occurring and can assist the pilot in diagnosing the event. For normal events, multi-sensory inputs assist the pilot in monitoring the event to ensure that aircraft parameters remain within their normal bounds. In most cases, there is no explicit training for the recognition of the meaning of these inputs. They are learned through experience with flying the aircraft.

How Sensory Deficiencies Affect Accidents of Unmanned Aircraft

Now that we have established that pilots of unmanned aircraft receive fewer types of sensory inputs than pilots onboard the aircraft, the next question is whether there is any evidence that this lack of sensory inputs for UAS pilots has led to accidents. Research that has looked at UAS accident causal factors has suggested that sensory deficiencies have played a role in UAS accidents (Tvaryanas et al., 2005). For example, as reported earlier, Tvaryanas et al. stated that 10% of UAS accidents across all services were influenced by a misperception of the location and/or attitude of the aircraft. Additionally, they found that 26.5% of the Predator accidents they reviewed had problems associated with the instrumentation and sensory feedback systems. However, for other military systems, the presence of sensory feedback as a factor in the accidents was not as readily apparent. Tvaryanas et al. speculate that the difference could be that Air Force UAS pilots are more likely to notice the lack of sensory information relative to manned aircraft because of their greater experience with manned aircraft operations. UAS pilots in other military branches are not required to have manned aircraft experience. However, just because UAS pilots do not report problems associated with a lack of sensory information does not mean that no such problems exist.

To expand on these data, a review was conducted of accident information that was reported by this author on several military UASs (Williams, 2004). Unfortunately, the accident reports that were used in the original study did not contain sufficient detail in all cases to make a definitive judgment regarding whether a lack of sensory information played a role in the accidents. For example, there were a large number of Pioneer accidents that were attributed to an electrical or mechanical failure. It was not known for those accidents how quickly the UAS pilots became aware of the failure and whether they might have been able to prevent the accident had they been given enough time to react to the circumstances. Nevertheless, the reports were analyzed to obtain a general indication of how prevalent a role the lack of sensory information played in the accidents.

Four systems were reviewed from the original data: Navy/Marine Pioneer; Army Shadow and Hunter; and Air Force Predator. Figure 2 shows the accident rate for each system where it was determined that a lack of sensory information played a role in the accident, as a percentage of the total number of accidents for that system and as a percentage of the number of accidents that were identified as related to human factors.

Looking at Figure 2, it is interesting to note that the percentage of Predator accidents in which a lack of sensory information contributed to the accident is very similar to the results reported in the Tvaryanas et al. study, especially given the fact that the 2 studies used different sets of accident data. However, whereas Tvaryanas et al. did not note any accidents related to a lack of sensory information for other UASs, the data from Williams (2004) showed that both the Shadow and Hunter UASs have higher percentages of sensory-related accidents (for

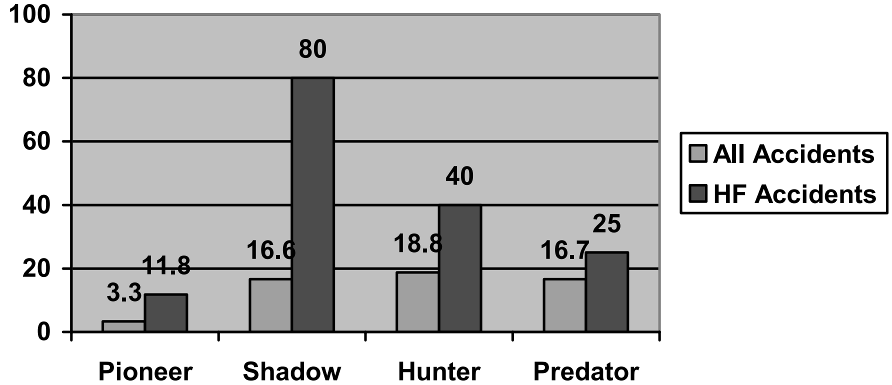

Figure 2. Percentage of accidents in which a lack of sensory information contributed.

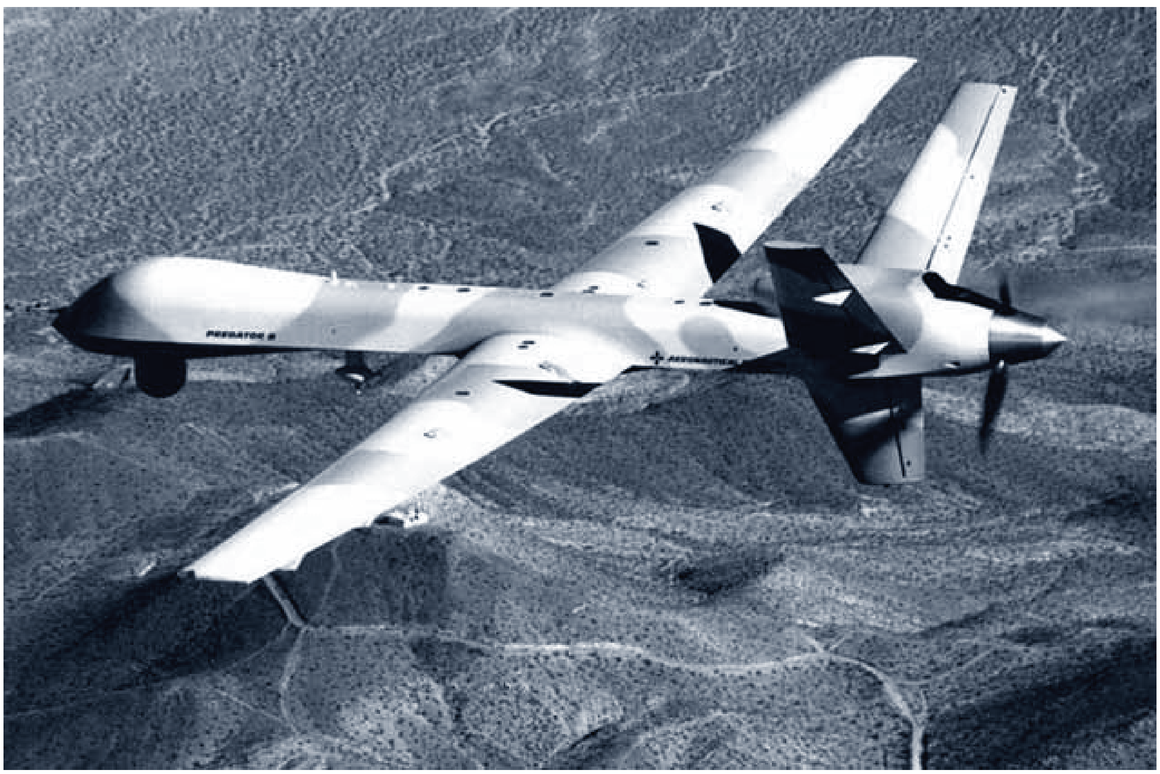

Figure 3. Predator B unmanned aircraft.

those accidents related to human factors). In particular, 4 out of 5 human factors-related Shadow accidents were considered to have been influenced to some degree by the lack of sensory information available to the Shadow UAS pilots. Although, as was mentioned, the data used for the studies were not the same, this is probably not the entire explanation. Unlike Tvaryanas et al.(2005), the data from Williams (2004) did not rely on pilot self-reporting, and so would not have been influenced by prior operational experience with manned aircraft as was noted earlier.

An example of a recent accident in which the lack of sensory information played a role was the April 2006 crash of a Predator B UA (Figure 3) in the Arizona desert. This accident occurred after the inadvertent shutting off of the engine by the pilot while trying to hand off control of the aircraft from the left to the right pilot station (Figure 4).

After the engine was first shut off, the aircraft nose dipped momentarily before onboard automation stabilized the descent. The dipping of the nose could be seen on the forward out-the-window view screen in the control station (lower left screen in Figure 4), but it was not accompanied by kinesthetic and vestibular inputs that the pilot of a manned aircraft would normally encounter. The pilot misinterpreted the dipping of the nose as a

Figure 4. Predator control station.

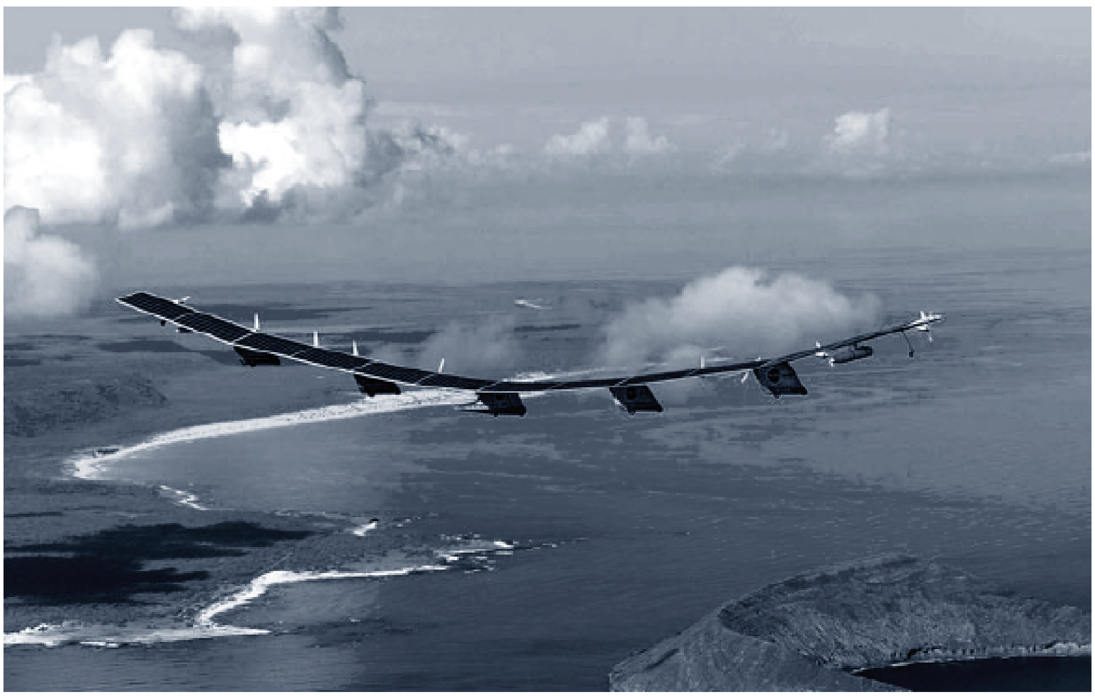

Figure 5. Helios UAS.

loss of data link from the control station to the aircraft. Earlier in this paper, it was shown that for manned aircraft a loss of engine is almost always accompanied by a change in sound, vestibular, and kinesthetic sensations. The Predator pilot, being an experienced manned aircraft pilot, might have misinterpreted the loss of the engine at least in part because the visual information presented in the forward out-the-window view (the dipping of the nose of the aircraft) was not accompanied by these other sensations, which is what the pilot of a manned aircraft would expect. One question that arises here is whether removing the forward out-the-window view might have changed the pilot's expectations in such a way that would have prevented a misinterpretation of the information, allowing the pilot to focus more on other available display indications that would have led to the correct diagnosis of the event.

Examples of Remediations From the Current UAS Inventory

For the most part, UAS manufacturers have done little in the way of compensating for the reduced sensory information available to the UA pilot, although the general trend toward automation can be considered a response to sensory information deficiencies. One example where a remediation was implemented was with the control station for the Helios UAS, manufactured by Aerovironment, Inc. (Figure 5).

An accident of a Helios occurred in June 2003 during a flight test. The aircraft flew into turbulence that exceeded the maximum capability of the aircraft, and it broke apart, crashing into the ocean and totally destroyed the aircraft (Noll et al., 2004; Williams, 2006).

As a result of that accident, a new display was added to the control station of the Helios that alerted the pilot to excessive stresses on the airframe. Whether the presence of the display would actually allow a pilot to respond appropriately to turbulence remains to be tested. However, there is no record of a Helios accident caused by turbulence since the inclusion of the display.

As mentioned earlier, one other method that UA manufacturers have adopted to compensate for reduced sensory information is the use of colors on the displays. For example, several systems will display certain information such as engine RPM or airspeed in yellow or red when those values fall outside of specified values. A loss of data link is signaled in the Hunter UA when the data link display turns orange (see Appendix A). A similar loss of data link in the Shadow UA is signaled by all of the flight displays turning orange.

While the use of color with textual information can effectively draw the attention of the pilot to abnormal flight parameters, it can lead to a loss of useful information at times. For example, for some systems, airspeed values are presented in text on the out-the-window display. These numbers will change to yellow and red when airspeed values exceed certain limits. This is useful information to the pilot; however, what is missing is an indication of the range of airspeeds that are within limitations and how quickly the values might be approaching those limits. With traditional cockpit instrumentation, these limits are indicated as colored arcs on the outside of the airspeed indicator. By coloring the text, some of the information provided by the arcs is now lost.

Research Efforts to Improve Sensory Information in Unmanned Aircraft

One means of coping with the loss or degradation of sensory information is through the use of other sensory modes or by the enhancement of visual displays. For example, researchers have suggested the use of haptic cues to enhance pilot awareness of events in the aircraft (Cheung et al., 2004; Draper, Ruff, Repperger, & Lu, 2000; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; Ruff, Draper, Lu, Poole, & Repperger, 2000; Sklar & Sarter, 1999). In particular, Draper and colleagues have suggested the use of haptic cues to indicate the onset of turbulence to operators of UA.

In the research of Draper et al. (2000), pilots received 4 types of warnings regarding the onset of turbulence: 1) visual; 2) visual with haptic; 3) visual with auditory; and 4) visual, haptic and auditory. The visual cue consisted of a perturbation of the nose-camera imagery consistent with a turbulence event. The haptic cue consisted of a 1-sec vibration of the pilot's joystick flight controller. The auditory warning was a 1-sec pure tone. All 3 cues began at the onset of the turbulence event.

The ability of the pilots to handle the in-flight turbulence was measured by how accurately they landed the aircraft, subjective assessments of awareness of the turbulence event on a scale of 1 to 5, accuracy in determining the primary turbulence motion (either along the pitch or roll axis), and by post-hoc workload subjective ratings. The results showed that the haptic feedback was an effective alerting cue, and that it was more effective than the visual or visual plus auditory cues.

However, while experiments testing this idea have been supportive, there are questions regarding how an onboard sensor would detect the initial onset of turbulence. To distinguish from a "bump" there would need to be some persistence and level of severity to the turbulence. How long would the turbulent motions need to persist, and how severe would they need to be to trigger an alarm? A turbulence alarm would run the risk of becoming a nuisance if it were constantly being triggered. One solution to this problem with haptic feedback is to focus on the use of such feedback as a general warning or alerting system (Sklar & Sarter, 1999).

A second type of sensory information that has been used to enhance UAS pilot information is proprioceptive information (Lam, Mulder, & van Paassen, 2007). In an experiment conducted by Lam et al., participants were asked to fly a simulated UAS around and among some buildings. Proprioceptive information was provided to the pilots by imposing control forces on the joystick that corresponded to the proximity of the aircraft to the buildings. Simply put, the pilot would find it more difficult to turn toward a building because of control forces on the joystick that would push the joystick in the opposite direction. The experiments showed that the imposition of this proprioceptive information resulted in fewer collisions.

A third type of sensory information that has been suggested is the use of spatial auditory displays (Simpson, Bolia, & Draper, 2004). More than just an auditory warning, a spatial auditory display provides position cues, as well as auditory cues to the operator. This allows for more complex coding of the cues and the presentation of more information. In addition, spatial auditory displays provide more of a sense of presence to the operator, immersing the operator virtually with a feeling of being with the aircraft. This sense of presence has implications for highly automated systems, where the operators might have a tendency to become out-of-the-loop.

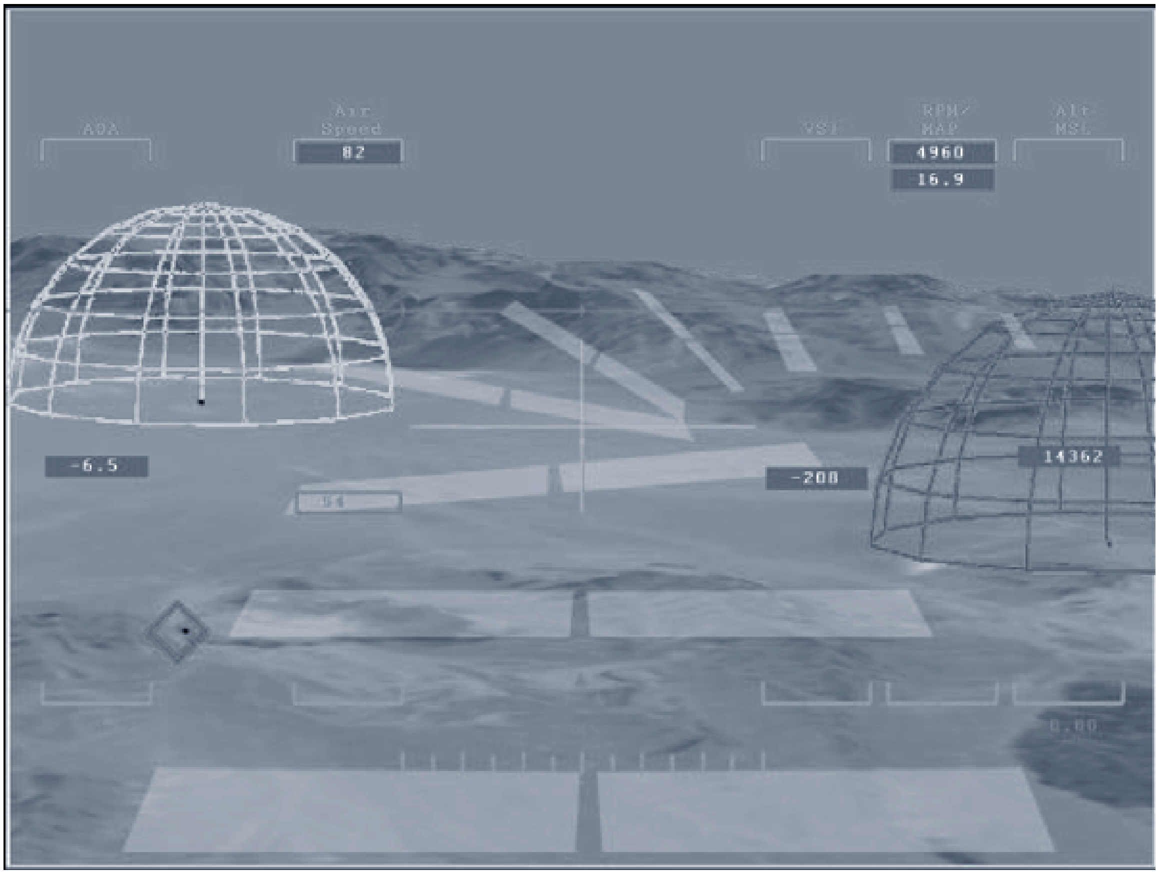

Figure 6. Synthetic threat and pathway information overlaid on a simulated nose camera imagery. From Calhoun et al., 2005. Reprinted with permission.

A fourth method for improving sensory information in unmanned aircraft that has been researched is through the enhancement of visual displays (Calhoun, Draper, Abernathy, et al., 2005; Draper, Nelson, Abernathy, & Calhoun, 2004). This method involves the use of enhanced or synthetic vision displays that are combined with an actual camera view of a scene to provide more and better information to the pilot and/or sensor operator. Figure 6 shows the use of synthetic vision information to enhance a camera view. Although much of this research has been focused on improving situation awareness for the payload operator, there is no reason why the same technology cannot also be used to assist the pilot.

An additional use of synthetic vision system information in a UA control station flight display is with a picture-in-picture concept (Calhoun et al., 2005). The approach with this concept is to present an actual camera view embedded in a larger synthetic visual display. The use of synthetic vision provides a larger field of view than would be available with a camera. In addition, synthetic imagery can include additional information, such as names of landmarks and boundaries that can be used to enhance the flight awareness of the pilot. Figure 7 demonstrates the use of the picture-in-picture concept.

The research efforts to enhance multi-sensory information in UASs have focused on the use of multi-sensory information in a display format, rather than an attempt to simulate actual multi-sensory experiences of the onboard pilot. There may be several reasons for this, but the strongest reason is probably the cost involved in simulation. The simulation of kinesthetic and vestibular inputs would require a moving platform, and the benefit to doing this is probably far outweighed by the cost, especially if other methods can be shown to effectively cue and/or inform the pilot of the status of the aircraft.

Federal Regulations Pertaining to Sensory Information in the Cockpit

One final issue that needs to be discussed is how well current cockpit design regulations address multi-sensory information requirements. There are several sections found in Title 14 of the Code of Federal Regulations (14 CFR) that identify sensory information requirements in the cockpit. These regulations do not necessarily pertain to visual or auditory information, though most do. In addition to the visual or auditory display of information, there are regulations that affect the information received by the pilot through other sensory modes. For example,

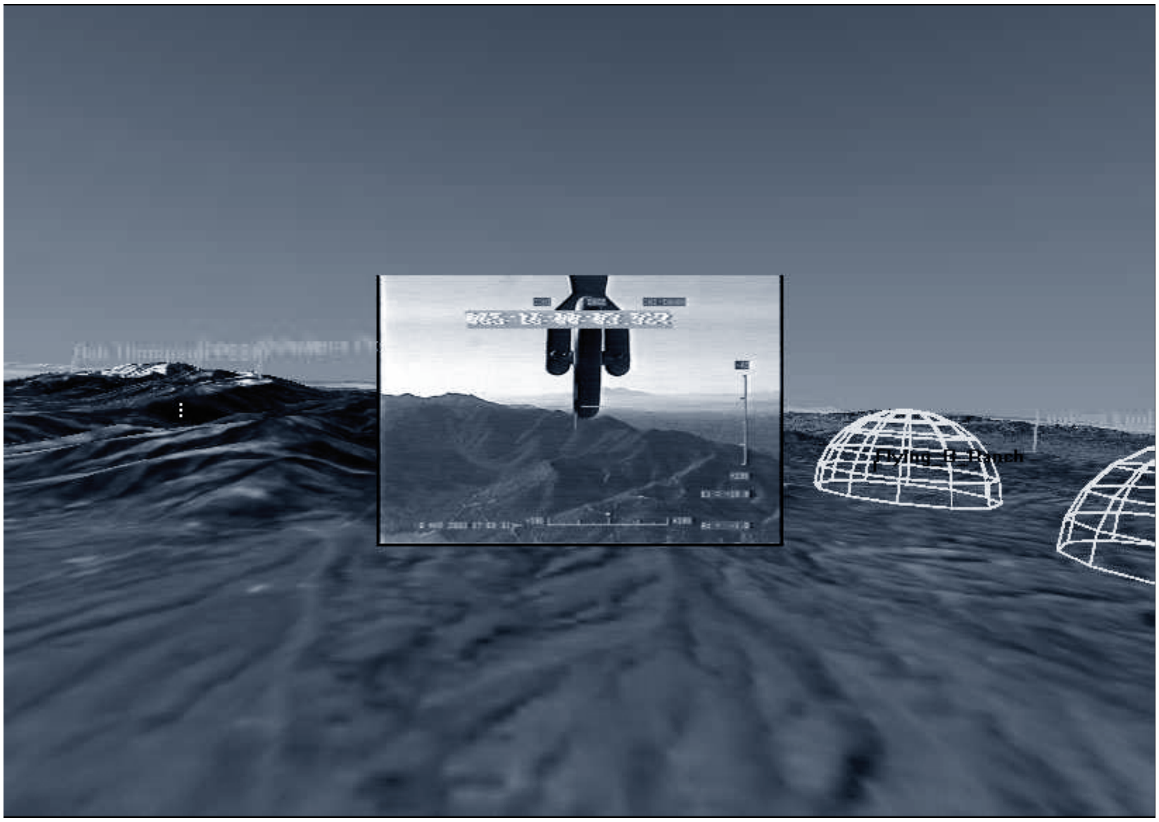

Figure 7. Use of synthetic imagery with a picture-in-picture to increase pilot awareness. From Calhoun et al., 2005. Reprinted with permission. Imagery courtesy of Rapid Imagery Software, Inc.

the regulation of the shape and texture of controls affects the haptic information available to the pilot. The regulation of physical force requirements for control movement affects the proprioceptive information available to the pilot. While the majority of the regulations pertain to cockpit displays and controls, some of the regulations deal with external (i.e., coming from outside the cockpit) information, such as the ability of the pilot to see outside the aircraft. In addition, 2 regulations pertain to the use of sensory information by the flight crew in regard to the recognition and correction of anomalous events. Table 9 lists the regulations that pertain to pilot sensory information. The complete 14 CFR text relevant to each of the sections can be found in Appendix B.

The first column in Table 9 indicates the type of sensory information that the regulation covers. This column is divided into 3 main sections. The first section lists regulations that pertain to sensory information in the cockpit. Cockpit information is further divided into visual, auditory, haptic, proprioceptive, and regulations that do not specify the mode of the information. Many of the regulations listed under "visual" do not specifically indicate that the sensory information needs to be visual in nature, but aspects of the regulation strongly imply the visual mode.

The second section lists regulations that pertain to sensory information external to the cockpit. This section is further divided into visual and proprioceptive information. The final section lists 2 regulations that pertain to the use of sensory information in recognizing anomalous events.

As should be expected, the majority of the regulations relate to the presentation of visual information to the pilot, primarily through aircraft displays. While the regulations focus on visual information, they do not explicitly exclude using other sensory modes that provide information to the pilot. For example, the use of a vibro-tactile (haptic) display is not proscribed by the regulations.

Probably one of the most relevant regulations to the current discussion is the last one listed in the table, 23.1309. Specifically, section 23.1309 directs that the design of warning cues for the pilot (crew) needs to include an assessment of the pilot's ability to determine the fault that is causing the need for that warning. For the design of unmanned aircraft control stations, this assessment needs an awareness of how the lack of sensory information alters the ability to determine anomalous aircraft conditions and what additional cues might need to be included in the control station to ensure the timely and accurate diagnosis of an anomaly.

Table 9. Federal regulations pertaining to pilot sensory information.

Type of Sensory Information	14 CFR Section	Notes
Cockpit Information		
Visual	23.1303	Flight and navigation instruments – some warning requirements are auditory
	23.1305	Powerplant instruments – some warnings have unspecified mode
	23.1311	Electronic displays
	23.1321	Arrangement and visibility of flight displays
	23.1322	Warning, caution, and advisory lights
	23.1326	Pitot heat indication systems – could use other modes but must include amber light
	23.1331	Instrument power indicator
	23.1335	Flight director mode indicator – selector switch position not acceptable
	23.1337	Fuel and oil quantity indications
	23.1351	Generator/alternator quantities and failure – failure warning not mode specific
	23.1381	Instrument lights
	23.1416	Pneumatic de-icer boot system function indication
	23.1543	Instrument markings: General
	23.1545	Airspeed indicator markings
	23.1549	Powerplant instrument markings
	23.1551	Oil quantity indicator markings
	23.1553	Fuel quantity indicator markings
	23.1555	Cockpit control markings
	91.205	Airworthiness instrument and equipment requirements
Auditory	23.703	Takeoff warning system
	23.729	Landing gear extension and retraction warnings and indicators – note that indicators are not mode-specific
	23.1431	Cockpit communications
Haptic	23.781	Control knob shape
Proprioceptive	23.143	Control force limits
	23.255	Control force response
Non-specific	23.679	Control system lock warning
	23.699	Wing flap position indicator
	23.207	Stall warning – requirement does not specify mode, but visual-only not allowed
	23.1309	Unsafe operating condition alerts
External		
Visual	23.773	Pilot compartment view
	23.775	Windshields and windows
	23.1383	Glare and halation from taxi and landing lights
	23.1419	Monitoring icing
Proprioceptive	23.251	Vibration and buffeting
Sensory Information Usage		
	63 App C	Flight engineer training course requirements
	23.1309	Development of crew warning cues must consider crew's capability of determining faults

CONCLUSIONS AND RECOMMENDATIONS

Sensory information that is available to the pilot of a manned aircraft includes visual out-the-window information, ambient auditory information, visual and auditory display information, vestibular, haptic, proprioceptive, and kinesthetic information. This analysis has shown that much of this information can be used for the detection and diagnosis of anomalous events during flight, as well as the monitoring of normal flight events. Additionally, most of this information serves to alert the pilot and direct attention to a particular aircraft system or condition. For most (but not all) types of events, the information from different modes reinforces each other in assisting the pilot in detecting and diagnosing.

The pilot of an unmanned aircraft, on the other hand, usually has far fewer pieces of information to work with, and usually this information is only in visual form. This puts the UA pilot at a disadvantage in being able to diagnose and respond to system anomalies. For many anomalies, the pilot must be looking at the right indications to be able to recognize and diagnose problems. In addition, the pilot has less sensory information available during the normal operation of the aircraft. The effect that this has on a pilot's awareness of flight parameters is not clear.

There is some evidence that this lack of sensory information has an impact on the safety of the flight. Analyses of UAS accidents suggest that between 15% and 25% of UAS accidents, across several systems, are due at least in part to a lack of sensory information. Additionally, when focusing on those accidents with a human factors component (i.e., eliminating accidents that are due to mechanical, electrical, or structural failures), the percentage of accidents that are at least in part due to sensory deficiencies is much higher.

Therefore, UAS designers, operators, trainers, regulators, etc., should consider pilot sensory deficiencies associated with UAS vs. manned aircraft. While more research is needed to determine the specific appropriate remediations, initial research suggests some alternatives that merit further investigation.

One recommendation is that UAS control station displays should include, when possible and economically feasible, warnings of critical anomalous events that involve more than one type of sensory mode (e.g., both an auditory and visual warning of critical anomalous events). The false alarm rate in the triggering of an auditory warning should be extremely low so that pilots are not tempted to ignore the warning or find some way to disable the warning. A corollary suggestion is that designers of UAS control station displays make greater use of multiple sensory modes in the presentation of aircraft flight parameters. For example, in addition to a visual display of engine RPM, there could also be a simulated engine noise that corresponds to the RPM setting. This would not have to be the actual noise from the aircraft engine transmitted to the control station (although that would provide additional useful information to the pilot) but could simply be an artificially generated sound that corresponds to the engine setting. The function of such auditory information would be to provide an indication of engine status that would not have to be consciously monitored on a regular basis by the pilot and to provide an auditory signal that would be directly related to a particular aircraft condition, instead of having a general warning that requires further diagnosis.

The use of other types of sensory input such as haptic input to flight controls could also be used to supplement visual and/or auditory information. However, for many UASs, the pilot does not necessarily have to maintain his/her hands on the controls at all times due to the highly automated nature of their control systems.

A second recommendation is that advantage should be taken of the available visual display space in alerting a pilot to a critical aircraft condition. Some systems have already incorporated this strategy by turning all of the primary flight displays orange to indicate a loss of data link. Because all UASs use electronic flight displays, there is no reason that critical flight information has to be restricted to a particular flight display. For example, even if there is a dedicated airspeed indicator, critical overspeed or underspeed values do not have to be restricted to that airspeed indicator. System designers could provide a visual warning that extends across a large portion of the normal visual scan to ensure that the pilot is fully aware of a potential or actual problem. This may help offset the lack of information available to the pilot from other sensory modes.

As mentioned earlier, there is a question in regard to whether the experience of piloting a manned aircraft is detrimental to piloting a UAS in terms of the recognition of anomalous events. It could be, based on the analysis in this paper, that this is the case. However, how a pilot transitions into an unmanned aircraft and the design of the control station would both have an effect on the pilot's ability to cope with a reduced set of sensory information types.

In addition, developers of pilot training should be aware of the critical importance of training pilots in the recognition and diagnosis of anomalous events. In particular, emphasis needs to be placed on the idea that the restriction in sensory information makes both recognition and diagnosis more difficult for the UAS pilot. The pilot should be fully aware of all the resources that are

available during the flight, and should have experience with various anomalous events through simulations. These simulations should require not only that the pilot know how to respond to a particular type of anomalous event but is also able to recognize and diagnose which type of anomalous event is occurring.

As was mentioned earlier, current regulations (i.e., 23.1309) direct that the design of warning cues for the pilot (crew) needs to include an assessment of the pilot's ability to determine the fault that is causing the need for that warning. Such an assessment requires a clear understanding of how the lack of sensory information alters the ability to determine anomalous aircraft conditions and what additional cues might need to be included in the control station to ensure the timely and accurate diagnosis of an anomaly.

Finally, there is a need for more empirical research on this topic. Some potential research questions include (from Mike Linegang, FAA, personal communication):

- Is there a difference in pilot abilities to detect and diagnose icing, engine failure, stall, turbulence, unusual attitude, and electrical system anomalies in manned and unmanned aircraft?
- Are the differences in performance large enough to require some type of safety mitigation?
- What aspects of the sensory deficiencies contribute most to differences in performance?
- How effective are various strategies for providing supplemental information?
- Is training an appropriate mitigation technique for some aspects of the sensory deficiency problem?
- Are there differences in sensory deficiency effects for UAS pilots that have no manned aviation background vs. UAS pilots that have experience in the sensory-rich environment of manned aviation?

Data from these types of studies will support definition of appropriate standards for UAS control stations and UAS pilots.

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APPENDIX A
UAS Sensory Information Interviews

Interview Questions for Documenting Sensory Information Available for Unmanned Aircraft Systems

Date: _____25 August 2006___________

System:________Hunter__________________ Manufacturer: ________NGC/IAI__________________

Position (e.g., pilot, engineer, etc.) _____pilot___________________ Years Experience w/system: ___13______

Datalink

1. What are the different kinds of links being used for UA control: for example, telecommand/up, telemetry/down, ATC communications?
C band datalink. Uplink commands, downlink telemetry and video.

2. What are the performance indicators for each link; that is, is there an indication of signal strength, error (dropout) rate, or simply a light indicating a connection?
Signal strength meters and warnings if up or downlink is lost.

3. How are these performance indicators displayed, including alerts? Include visual, aural, other, and the alert criteria (e.g., elapsed time) if known.
Meter on the ground station display. Also a warning for lost or weak up or down link and total loss of link plus return home warning.

4. In the event of lost telemetry (i.e., downlink of aircraft parameters), what happens to the information (e.g., attitude) at the control station? For example, is it extrapolated for a fixed time? Does it freeze at the last known state? Do the displays blank?
The display is frozen.

5. What is the normal system response to a lost link? That is, what is the aircraft supposed to do under lost link events?
Lost uplink will put the AV in a Return Home mode. It will fly at a preset airspeed and altitude to a designated point. If link is not regained it will circle there until it runs out of gas then deploy a recovery parachute.

6. During operation, how often are there link-related issues? Are link alerts common? Is it normal to have telemetry drop-outs for, say, 10 seconds? Is a pre-programmed procedure to regain link or return-to-base a rare event?
There are occasional short instances of link loss, both up and down during normal operations specifically at really close ranges or at the edge of the link range limits, often caused by maneuvering. Not often do they last for 10 seconds. Mostly just momentary hits.

7. What type of training is given to system pilots for recognizing lost link?
Standard part of training. Simulated link loss situations are practiced. Students are taught to manipulate the uplink to attempt to re-establish it after uplink loss and we practice “no report” recoveries if downlink is lost.

Engine Failure

1. What are the performance indicators for engine function (e.g., rpm, manifold pressure, etc.)?
RPMs, Oil temp, CHT (cylinder head temp), bus voltage plus written warnings for oil pressure.

2. In the event of an engine failure, how do these performance indicators react, including aural alerts?

In newer software versions the software changes the color of the readout depending on its value. For example, normal range values are green but if it gets into the caution zone the readout changes to yellow, then red for the danger zone.

3 What type of training is given to system pilots for recognizing an engine failure?
Normal part of training to practice engine fail or overheat situations. A good instrument scan is essential to recognize a problem if display is not color-coded or no warnings are displayed until the danger zone is reached that may generate a warning. Symptoms of various problems are taught and operators are trained to watch for them.

In-Flight Icing

1. What indications would the pilot receive in the control station if the aircraft were to experience in-flight icing?
The Hunter has no ice sensors. This can be very difficult to spot. A loss of altitude with an increase of engine rpms to try to maintain commanded altitude could be a good clue. Knowing the weather conditions and forecasts should also be a clue. If the pitot system ices up it can cause loss of pitch control. The onboard camera system can be used to look at leading edges to check for ice buildup. In severe cases the camera lens will freeze over and there will be no useable video. Prevention is best here. Know the freezing level and avoid visible moisture.

2. What type of training is given to system pilots for recognizing in-flight icing?
Weather training and avoidance primarily. Back up modes to the pitot (airspeed sensor) system are practiced.

Stall

1. What indications would the pilot receive in the control station if the aircraft were to experience a stall?
Slow airspeed, excessive pitch, wing rock, loss of altitude. No specific warnings, just recognition of the condition on the instrument panel.

2. What actions would the pilot make to recover from a stall?
Increase airspeed, which lowers pitch. Increase altitude to raise rpms.

3. What type of training is given to system pilots for recognizing a stall?
Instrument scan.

Turbulence

1. What indications would the pilot receive in the control station if the aircraft were to experience moderate to severe turbulence?
Attitude indicator would display excessive pitch and roll maneuvers. If really strong, a VGU (vertical gyro unit) failure if the VGU limits are exceeded.

2. What actions would the pilot make to the aircraft under such conditions?
Adjust airspeed to the maneuver speed and change altitude and try to fly away from the area.

3. What type of training is given to system pilots for recognizing turbulence?
Instrument scan to watch for excessive movement. Weather training.

Interview Questions for Documenting Sensory Information Available for Unmanned Aircraft Systems

Date: 28 August 2006

System: Hunter RQ-5A / MQ-5B Manufacturer: Northrop Grumman

Position (e.g., pilot, engineer, etc.) Pilot Years Experience w/system: 12 Years

Datalink

1. What are the different kinds of links being used for UA control: for example, telecommand/up, telemetry/down, ATC communications?

C-Band. ATC communications has nothing to do with UA control. We communicate with ATC on UHF, VHF, and or FM.

2. What are the performance indicators for each link; that is, is there an indication of signal strength, error (dropout) rate, or simply a light indicating a connection?

We have "thermometer" style gauges with corresponding digital numbers for uplinks (primary and secondary), downlinks (primary and secondary), and reflective power (primary and secondary). The downlink displays will turn orange in color if the link quality degrades below a preset limit.

3. How are these performance indicators displayed, including alerts? Include visual, aural, other, and the alert criteria (e.g., elapsed time) if known.

Uplink / Downlink "thermometer" style gauges are displayed on 2 panels that are directly related to the primary and secondary link functions. If link quality drops below the preset limit or a link related problem exists, a warning will appear in the warnings panel indicating the active warning(s). Warnings that are related to a link level display parameter type warnings which indicate that a level has been exceeded, the current level, and the worst level. All warnings in the Hunter system stay illuminated until the warning condition no longer exists at which time the pilot must take action to "refresh" the warning list.

4. In the event of lost telemetry (i.e., downlink of aircraft parameters), what happens to the information (e.g., attitude) at the control station? For example, is it extrapolated for a fixed time? Does it freeze at the last known state? Do the displays blank?

If the Hunter UAV loses downlink, the appropriate downlink warnings will appear in the warnings panel and the downlink displays turn orange indicating a total downlink loss exists. The telemetry will freeze at the last reported values. A new AV position icon will appear and move in the last reported direction and airspeed. The standard icon will remain frozen at the last reported position. When downlink is regained all telemetry is updated to the current reports.

5. What is the normal system response to a lost link? That is, what is the aircraft supposed to do under lost link events?

If the Hunter UAV loses downlink the AV will still respond to all commands but will not report its actions until downlink is regained. If the Hunter UAV loses uplink the AV will either enter its "Return Home" plan or it will enter "Glide" mode depending on the scenario. "Return Home" is used during all loss of uplink scenarios except for approximately the first thirty seconds after takeoff and the last thirty seconds during landing. While in "Return Home" the Hunter UAV flies to a specified coordinate(s) at a specified altitude and airspeed. Upon arrival the AV enters a left hand orbit around a specified coordinate at a specified altitude and airspeed until uplink is regained or until it runs out of gas at which time the Emergency Recovery System (parachute) is deployed.

6. During operation, how often are there link-related issues? Are link alerts common? Is it normal to have telemetry drop-outs for, say, 10 seconds? Is a pre-programmed procedure to regain link or return-to-base a rare event?

During normal operations, true link issues are not common. We occasionally see intermittent downlink during local flight operations because of the attitude and altitude of the AV. Normally the warnings will appear for a few seconds and then go away. It is not normal for us to see downlink losses for more than a few seconds depending on the situation. If we are flying near the limit of our line of site because of terrain or range, intermittent link losses will be the first indication. As described above, Hunter uses a “Return Home” plan to return to base during an uplink loss. While in “Return Home” the AV uses logic in an attempt to regain uplink on its own.

7. What type of training is given to system pilots for recognizing lost link?

Pilots are given several simulator flights where virtually all failures / responses can be discussed, demonstrated, and performed. During flight training the pilot’s system knowledge to include data link management is verbally tested. Instructors can also purposely turn off uplink / downlink to demonstrate the effects on the AV.

Engine Failure

1. What are the performance indicators for engine function (e.g., rpm, manifold pressure, etc.)?

The Hunter UAV reports RPM, Oil Temp, Cylinder Head Temp, Fuel Flow, and Bus Voltage or RPM, Water Temp, Exhaust Gas Temp, Fuel Flow and Bus Voltage depending on which model is being flown.

2. In the event of an engine failure, how do these performance indicators react, including aural alerts?

If the Hunter UAV experiences an engine failure the RPM digital report turns red and a few red warnings directly related to the engine failure appears in the warnings panel. Forward and or aft engine cut, Forward and or AFT RPM <500 Current: XX Worst: YY, Forward and or Aft Generator Fail, Forward and or Aft Oil Pressure Failure, and Fuel Pump Failure. (The and or type warnings are actually individual warnings that I combined for your sake)

3. What type of training is given to system pilots for recognizing an engine failure?

As described above with regard to the lost link training, a similar training approach trains pilots to recognize and react to an engine(s) failure. During simulator flights the instructor will cut an engine(s) to discuss, demonstrate, and perform the proper response to an engine failure. During flight training engines are not cut due to the risk incurred however instructors regularly “simulate a single / dual engine failure” to ensure the student reacts appropriately. Instructors also give scenarios based on the AV range, altitude, and the field elevation to ensure the pilot knows how to figure out if the AV is capable of returning to the landing site or if the parachute needs to be deployed.

In-Flight Icing

1. What indications would the pilot receive in the control station if the aircraft were to experience in-flight icing?

The Hunter UAV doesn’t have a deicing capability. Pitch oscillations as the AV autopilot attempts to maintain the commanded airspeed, inability to maintain altitude as ice builds on the AV, and or loss of control of the AV. The IR camera can be used to determine if ice is building on the AV.

2. What type of training is given to system pilots for recognizing in-flight icing?

Our pilots are trained that flight into known or forecasted icing conditions is prohibited. Our pilots are trained that if the AV is flown into icing conditions the aircraft could start pitch oscillations due to the Pitot tube freezing and the commanded airspeed not being achieved. The aircraft might also start to have difficulty in maintaining altitude do to ice build up on the wing. Eventually the AV could become uncontrollable and force the pilot to deploy the parachute. The IR camera can also be used to look at the

AV and determine if icing is a factor. If icing is suspected the pilot should descend if able. Avoid bank angles or greater than 15 degrees and command 70 knots. Avoid abrupt airspeed command changes.

Stall

1. What indications would the pilot receive in the control station if the aircraft were to experience a stall?

There are no specific stall indications the pilot would receive in the control station. The pilot could notice a loss of control however might not be able to determine if it was due to a stall.

2. What actions would the pilot make to recover from a stall?

Assuming the AV became uncontrollable; the pilot would match commands and reports and determine if the AV has become controllable. Matching commands in an uncontrollable situation would typically result in increasing the airspeed since the AV would likely be descending at an airspeed greater than was being flown prior to the stall.

3. What type of training is given to system pilots for recognizing a stall?

The Hunter UAV system prevents the pilot from stalling the AV in most cases when the internal pilot is in control. The bank angle and airspeed commands are limited to values that would prevent a stall in most cases. The external pilot is used for takeoff and landings and has different limits to commands and is more susceptible to stalling due to the airspeeds required to takeoff and land. All of the pilots are trained on reading the AV performance charts which include the stall speed at various weights and bank angles.

Turbulence

1. What indications would the pilot receive in the control station if the aircraft were to experience moderate to severe turbulence?

Fluctuations in the attitude indicator and pitch (more than 5 degrees), roll, and climb rate reports. Severe turbulence could cause damage to the AV resulting in the AV becoming uncontrollable.

2. What actions would the pilot make to the aircraft under such conditions?

Avoid bank angles or greater than 15 degrees and command 70 knots. Avoid abrupt airspeed command changes. Depart the area where the turbulence is being experienced.

3. What type of training is given to system pilots for recognizing turbulence?

Pilots are trained that flight into known or forecasted severe turbulence is prohibited and what to do if they experience turbulence during a flight. They are also trained that turbulence can lead to structural damage and lead to a loss of control of the AV.

Interview Questions for Documenting Sensory Information Available for Unmanned Aircraft Systems

Date: 21/09/2006

System: TWINaIR

Manufacturer: TeleFlight Technologies LTD

Position (e.g., pilot, engineer, etc.) CTO

Years Experience w/system: >20

Datalink

1. What are the different kinds of links being used for UA control: for example, telecommand/up, telemetry/down, ATC communications?

We are using a completely redundant unit for data/control that works as follows:
We have two data/control systems that can operate in frequencies starting at 400MHz all the way to 5.8GHz. The unit has three data link options that can be set by the user

Line of sight 900MHz-5.8GHz
Beyond Line of sight 390-450MHz short-mid range
Beyond Line of sight Urban area GSM GPRS
Beyond Line of sight Long range satellite

All up and down links can be configured individually to work on different frequencies, we use FHSS systems for better noise immunity.
We use automatic bandwidth and output power setting by the radio base-band.

2. What are the performance indicators for each link; that is, is there an indication of signal strength, error (dropout) rate, or simply a light indicating a connection?

All links have an RSSI indication as well as bad/good massage count, we also use an alarm indication at the GCS. As mentioned above, as soon as we have an indication that the BER is bad and the RSSI is bad we take action to try and improve the link.

If we completely lose the link we have a failsafe model that we believe is bulletproof.

3. How are these performance indicators displayed, including alerts? Include visual, aural, other, and the alert criteria (e.g., elapsed time) if known.

The indications for loss of signal are both audible and visual, and are also divided into critical and noncritical categories. Each category has min and max limits defined by the manufacturer of the equipment and can be defined per UV system depending on the performance required.

4. In the event of lost telemetry (i.e., downlink of aircraft parameters), what happens to the information (e.g., attitude) at the control station? For example, is it extrapolated for a fixed time? Does it freeze at the last known state? Do the displays blank?

When loss of telemetry occurs we do both extrapolation of the estimated location of the UV and marking of the last known location of the UV.
Within the UV a complete failsafe procedure starts to operate in order to try and bring the UV back on line and if not successful bring the UV home safely.

5. What is the normal system response to a lost link? That is, what is the aircraft supposed to do under lost link events?

We start by reducing the bandwidth, and increasing the RF output power while in parallel performing a BIT of the COM system. The system switches between the different frequencies based on a known sequence and time algorithm, switching to GSM or even satellite based on the equipment installed on the UV.
It depends on the program. If all the indications from the mechanical systems seem to be OK we can gain altitude to regain communications and continue the mission or go back home.
In order to gain altitude we operate a see and avoid system, or if operating in an urban area, we have a data base of all approved UV and civil flights to make sure that we don't interfere. We can also instruct the UV to move to a safe landing base on the map database loaded into the mission computer.
There is a lot more. If you need to know please let me know.

6. During operation, how often are there link-related issues? Are link alerts common? Is it normal to have telemetry drop-outs for, say, 10 seconds? Is a pre-programmed procedure to regain link or return-to-base a rare event?

Although we operate UV's almost every day we rarely get a COM fail problem, even in urban areas or jammed areas.
See above for the second question

7. What type of training is given to system pilots for recognizing lost link?

Because we think that command and control is one of the most important features for a pilot we invest a lot in improving his skills to recognize a problem before it occurs and try to fix it.
We also make sure that the GCS indications are clear and loud. In any case of failure we are guiding the pilot via a driven menu that is displayed and verbally sounded that will take the pilot through the correct procedure.

Engine Failure

1. What are the performance indicators for engine function (e.g., rpm, manifold pressure, etc.)?

Depending on the TYPE of the UV Electrical or combustion (GAS) we have different types of sensors starting with RPM battery gas flow etc.
We also calculate the point of no return and clearly indicate it to the pilot at all times. We are both calculating the Point of no return during the mission planning and actually during the mission.
On combustion engines we have an automatic procedure to keep the engine running embedded into the control computer and the means to start the engine in the air with the correct procedure for different engines.

2. In the event of an engine failure, how do these performance indicators react, including aural alerts?

In case of an engine cut the indicators will both flash and will make a sound as well as the failing part will be illuminated on the UV image on the main screen

3 What type of training is given to system pilots for recognizing an engine failure?

We think that mechanical is one of the most common failures, and the most difficult to recover from. So we invest a lot in improving pilot's skills to recognize a problem before it occurs and try to fix it. Or if it occurs we give him help via driven menus and verbal help for each problem.
We also make sure that the GCS indications are clear and loud.
In any case of failure we are guiding the pilot via a driven menu that is displayed and verbally sounded that will take the pilot through the correct procedure.

In-Flight Icing

1. What indications would the pilot receive in the control station if the aircraft were to experience in-flight icing?

We have never had to deal with icing.

2. What type of training is given to system pilots for recognizing in-flight icing?

Stall

1. What indications would the pilot receive in the control station if the aircraft were to experience a stall?

We have different procedures to deal with stall conditions depending on altitude and population conditions.
The AP will recognize and GCS will indicate that the UV is coming close to stalling and will either recommend or will take over depending on the mode that the AP is in at the time of the stall.
As stall is an emergency procedure the pilot is trained to handle such a problem, and is given all the required help from the GCS both via driven menus and verbally.
The GCS will indicate the altitude, speed, RPM, and turn rate of the UV and will give proper instructions based on the UV parameter data base stored in the control computer.

2. What actions would the pilot make to recover from a stall?

It really depends on the position and altitude of the UV and the conditions of the propulsion system.

3. What type of training is given to system pilots for recognizing a stall?

As Stall is an emergency procedure the pilot is well trained in all the stall possibilities and what he needs to do in order to regain air speed and normal flight conditions.
I can elaborate more about each specific condition if you need.

Turbulence

1. What indications would the pilot receive in the control station if the aircraft were to experience moderate to severe turbulence?

No real indication is given to the AP of the UV regarding severe turbulence but we can add this indication from the ground and update the data base for each zone.

2. What actions would the pilot make to the aircraft under such conditions?

The actions depend on the speed and altitude of the UV.
I can elaborate more if required

3. What type of training is given to system pilots for recognizing turbulence?

As turbulence is not considered an emergency procedure the pilot is given notice for the existence of such turbulence, and an indication of how to behave in different airflow conditions.
I can elaborate more about each specific condition if you need.

Unusual Attitude

1. What indications would the pilot receive in the control station if the aircraft were to experience an unusual attitude?

There are a large number of alarms indicating loss of altitude. The indication is both visual and verbal, and it will appear immediately as such an action takes place.
A bunch of recovery actions are taken in the AP to recover from such an emergency.
If telemetry is in place the pilot can gain control over the UV and safely control the UV to a safe altitude.
The alarms are going to be activated on every screen so no matter what the pilot is doing he will know that an unusual attitude has occurred. The pilot can set the alarm margins as he feels.

2. What actions would the pilot make to the aircraft under such conditions?

It depends on if the pilot is in control or the AP is in control, but there are a couple of known procedures that enable the pilot to control the UV for both increasing the altitude and decreasing the altitude.

3. What type of training is given to system pilots for recognizing unusual attitude?

The pilot is trained to understand the alarms and to decide what is required to do in order to regain normal flight conditions.

Loss of Onboard Electrical Power

1. What indications would the pilot receive in the control station if the aircraft were to experience a loss of electrical power?

In case of a complete power loss the pilot is going to see that the communication with the UV is not in order.

2. What actions would the pilot make to the aircraft under such conditions?

There is a little that the pilot can do for a total electrical failure, but the onboard back up system will perform couple of actions to resolve the problem without any human losses.

3. What type of training is given to system pilots for recognizing a loss of electrical power?

As the pilot cannot do anything in this condition no training is given but to report the last location of the UV and condition of the UV before it was lost.

Interview Questions for Documenting Sensory Information Available for Unmanned Aircraft Systems

Date: ___9/26/06_____________

System:__Skyeye® UAV________________________ Manufacturer: ___BAE Systems_____________

Position (e.g., pilot, engineer, etc.) Program Manager/Safety Observer/Engineer__________________ Years Experience w/system: _18____

Datalink

1. What are the different kinds of links being used for UA control: for example, telecommand/up, telemetry/down, ATC communications?
Redundant uplink command (clear L band, frequency hopping C band). Single downlink (S band) with telemetry and real time digitized and scrambled video.

2. What are the performance indicators for each link; that is, is there an indication of signal strength, error (dropout) rate, or simply a light indicating a connection?
Uplink has a green or red light to show presence or absence of uplink.
An analog bar shows uplink signal strength
Downlink has a green or red light to show presence or absence of downlink.

3. How are these performance indicators displayed, including alerts? Include visual, aural, other, and the alert criteria (e.g., elapsed time) if known.
Visual (color and graph)

4. In the event of lost telemetry (i.e., downlink of aircraft parameters), what happens to the information (e.g., attitude) at the control station? For example, is it extrapolated for a fixed time? Does it freeze at the last known state? Do the displays blank?
If telemetry is lost, the displays freeze at last known good data. No extrapolation, no "blanking" of display.

5. What is the normal system response to a lost link? That is, what is the aircraft supposed to do under lost link events?
The AV flies straight ahead for 10 seconds. If link is not re-established it enters the pre-programmed waypoint table. If no table is loaded, the AV goes home and circles overhead for a predetermined length of time. After this loiter, if link is not reestablished, the AV will automatically land at the predetermined location (could be "home" or some other location). Alternately, the AV can be preprogrammed to fly to an alternate point and deploy the unguided parachute. All "predetermined" points, including the choice of autolanding or parachute deployment, can be made during flight if uplink and downlink are both acceptable.

6. During operation, how often are there link-related issues? Are link alerts common? Is it normal to have telemetry drop-outs for, say, 10 seconds? Is a pre-programmed procedure to regain link or return-to-base a rare event?
The frequency of link alerts depends on range, altitude, and topography. Normal diligence in mission planning reduces frequency of link problems. Total loss of link and return to base without reestablishing link is a very rare event.

7. What type of training is given to system pilots for recognizing lost link?
Approximately 16 hours of simulator time with instructor-inserted faults, including loss of uplink or downlink or both.

Engine Failure

1. What are the performance indicators for engine function (e.g., rpm, manifold pressure, etc.)?
There is a vertical, colored bar graph, with a digital readout for engine RPM. There is a digital readout for fuel flow and fuel remaining.

2. In the event of an engine failure, how do these performance indicators react, including aural alerts?

Upon engine failure, the RPM bar graph drops to the bottom of the scale, the display turns red, and the digital readout goes to zero. Fuel flow drops to zero and goes red. If the engine kill has been commanded, the bar graph goes to full scale, the display turns red, and the digital readout goes to full scale. The "ENGINE KILL indicator also illuminates red. No aural indicator

3 What type of training is given to system pilots for recognizing an engine failure?

Approximately 16 hours of simulator time with instructor-inserted faults, including engine out, engine stuck at present position, engine stuck at full, engine operating normally with no engine RPM indication

In-Flight Icing

1. What indications would the pilot receive in the control station if the aircraft were to experience in-flight icing?
None – this AV operates in a non-icing environment

2. What type of training is given to system pilots for recognizing in-flight icing?

Stall

1. What indications would the pilot receive in the control station if the aircraft were to experience a stall?

Same as a manned aircraft – if flying in "manual mode" (direct control of the flight surfaces), the controls get less effective as stall approaches. At stall, the nose drops and airspeed rises to recover. Stall in this AV is very gentle. There is no dedicated stall warning. In autopilot modes (the standard flight modes), the autopilot prevents conditions that could result in a stall. The airspeed is presented in an analog dial gauge. The gauge is colored in segments. Green is the normal operating range. Yellow is the highest allowable speed range. Red is overspeed. White is below the allowable operating range.

2. What actions would the pilot make to recover from a stall?

Same as a manned aircraft – if flying in "manual mode" (direct control of the flight surfaces), the controls get less effective as stall approaches. The pilot can drop the nose and add power to recover from stall. Stall in this AV is very gentle

3. What type of training is given to system pilots for recognizing a stall?

Approximately 16 hours of simulator time with instructor-inserted faults, including flying in manual mode with no autopilot aiding. Stalls are induced for pilot familiarity.

Turbulence

1. What indications would the pilot receive in the control station if the aircraft were to experience moderate to severe turbulence?
No telemetry indication, but turbulence can be seen in the downlinked video if the payload is in certain modes.

2. What actions would the pilot make to the aircraft under such conditions?

None – the AV is rated for plus/minus 10g

3. What type of training is given to system pilots for recognizing turbulence?

Approximately 16 hours of simulator time with instructor-inserted faults, including moderate turbulence and gusting winds on landing

Unusual Attitude

1. What indications would the pilot receive in the control station if the aircraft were to experience an unusual attitude?

Aside from the "pilot's view" camera, the most prominent instrument is the combination compass/artificial horizon. The AV icon would duplicate the unusual attitude. Aside from the AV icon, the artificial horizon is split into blue/brown (sky/earth). Unusual attitudes are immediately apparent.
In the event of gyro failure, the display can be random (usually hard over one way or the other). An unusual attitude can be recognized or disregarded by the pilot using the onboard electro-optical camera in "pilot's view".

2. What actions would the pilot make to the aircraft under such conditions?

If flying in manual mode, the pilot can engage any of the autopilot modes and the AV will self correct. If flying in one of the autopilot modes and a failure results in an unusual attitude, the pilot can take full control in manual mode and attempt to fly the AV manually with no autopilot aiding. Alternately, or if the pilot's view camera and artificial horizon disagree and the pilot can't discern which is correct, the pilot can command emergency parachute deployment.

3. What type of training is given to system pilots for recognizing unusual attitude?

Approximately 16 hours of simulator time with instructor-inserted faults, including various combinations of failed instruments (a failed aileron servo can drive a bank until the pilot applies enough stick to compensate with the other aileron, a failed gyro in one of the autopilot modes can result in a random display with unusual attitude).

Loss of Onboard Electrical Power

1. What indications would the pilot receive in the control station if the aircraft were to experience a loss of electrical power?

There is a horizontal bar graph with a pointer and a digital readout for system voltage. If system voltage falls below a predetermined level, the display turns red. The pilot is trained to recognize proper system voltage.

2. What actions would the pilot make to the aircraft under such conditions?

At first loss of on-board electrical generation, emergency procedures call for the pilot and navigator to identify and navigate to a safe landing area. Once the voltage falls further to a lower predetermined level, the emergency procedures instruct the pilot to command an emergency parachute deployment.

3. What type of training is given to system pilots for recognizing a loss of electrical power?

Approximately 16 hours of simulator time with instructor-inserted faults, including alternator failure.

APPENDIX B
Federal Regulations Pertaining to Pilot Sensory Information

Note that these regulations were all taken from the Code of Federal Regulations (CFR) Part 14. Also, in listing the regulation, sometimes the entire regulation is not listed for purposes of saving space if portions of the regulation were not considered relevant to the issue of pilot sensory information. These deletions are noted by an ellipsis (…).

Controllability and Maneuverability
23.143 General.

(a) The airplane must be safely controllable and maneuverable during all flight phases including—
(1) Takeoff;
(2) Climb;
(3) Level flight;
(4) Descent;
(5) Go-around; and
(6) Landing (power on and power off) with the wing flaps extended and retracted.
(b) It must be possible to make a smooth transition from one flight condition to another (including turns and slips) without danger of exceeding the limit load factor, under any probable operating condition (including, for multiengine airplanes, those conditions normally encountered in the sudden failure of any engine).
(c) If marginal conditions exist with regard to required pilot strength, the control forces necessary must be determined by quantitative tests. In no case may the control forces under the conditions specified in paragraphs (a) and (b) of this section exceed those prescribed in the following table:

Values in pounds force applied to the relevant control	**Pitch**	**Roll**	**Yaw**
(a) for temporary application:			
Stick	60	30	
Wheel (Two hands on rim)	75	50	
Wheel (One hand on rim)	50	25	
Rudder Pedal			150
(b) For prolonged application	10	5	20

23.155
Elevator control force in maneuvers.

…
(c) There must be no excessive decrease in the gradient of the curve of stick force versus maneuvering load factor with increasing load factor.

Sec. 23.207
Stall warning.
(a) There must be a clear and distinctive stall warning, with the flaps and landing gear in any normal position, in straight and turning flight.
(b) The stall warning may be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself.
[(c) During the stall tests required by Sec. 23.201(b) and Sec. 23.203(a)(1), the stall warning must begin at a speed exceeding the stalling speed by a margin of not less than 5 knots and must continue until the stall occurs.
(d) When following procedures furnished in accordance with Sec. 23.1585, the stall warning must not occur during a takeoff with all engines operating, a takeoff continued with one engine inoperative, or during an approach to landing.
(e) During the stall tests required by Sec. 23.203(a)(2), the stall warning must begin sufficiently in advance of the stall for the stall to be averted by pilot action taken after the stall warning first occurs.
(f) For acrobatic category airplanes, an artificial stall warning may be mutable, provided that it is armed automatically during takeoff and rearmed automatically in the approach configuration.

Sec. 23.251
Vibration and buffeting.

There must be no vibration or buffeting severe enough to result in structural damage, and each part of the airplane must be free from excessive vibration, under any appropriate speed and power conditions up to V_D/M_D. In addition, there must be no buffeting in any normal flight condition severe enough to interfere with the satisfactory control of the airplane or cause excessive fatigue to the flightcrew. Stall warning buffeting within these limits is allowable.

23.679
Control system locks.

If there is a device to lock the control system on the ground or water:
(a) There must be a means to—
(1) Give unmistakable warning to the pilot when lock is engaged; or
(2) Automatically disengage the device when the pilot operates the primary flight controls in a normal manner.
(b) The device must be installed to limit the operation of the airplane so that, when the device is engaged, the pilot receives unmistakable warning at the start of the takeoff.
…

23.699

Wing flap position indicator.

There must be a wing flap position indicator for—
(a) Flap installations with only the retracted and fully extended position, unless—
(1) A direct operating mechanism provides a sense of "feel" and position (such as when a mechanical linkage is employed); or
(2) The flap position is readily determined without seriously detracting from other piloting duties under any flight condition, day or night; and
(b) Flap installation with intermediate flap positions if—
(1) Any flap position other than retracted or fully extended is used to show compliance with the performance requirements of this part; and
(2) The flap installation does not meet the requirements of paragraph (a)(1) of this section.

23.703

Takeoff warning system.

For commuter category airplanes, unless it can be shown that a lift or longitudinal trim device that affects the takeoff performance of the aircraft would not give an unsafe takeoff configuration when selection out of an approved takeoff position, a takeoff warning system must be installed and meet the following requirements:
(a) The system must provide to the pilots an aural warning that is automatically activated during the initial portion of the takeoff role if the airplane is in a configuration that would not allow a safe takeoff. The warning must continue until—
(1) The configuration is changed to allow safe takeoff, or
(2) Action is taken by the pilot to abandon the takeoff roll.
(b) The means used to activate the system must function properly for all authorized takeoff power settings and procedures and throughout the ranges of takeoff weights, altitudes, and temperatures for which certification is requested.

23.729

Landing gear extension and retraction system.

(a) *General.* For airplanes with retractable landing gear, the following apply:
…
(e) *Position indicator.* If a retractable landing gear is used, there must be a landing gear position indicator (as well as necessary switches to actuate the indicator) or other means to inform the pilot that each gear is secured in the extended (or retracted) position. If switches are used, they must be located and coupled to the landing gear mechanical system in a manner that prevents an erroneous indication of either "down and locked" if each gear is not in the fully extended position, or "up and locked" if each landing gear is not in the fully retracted position.
(f) *Landing gear warning.* For landplanes, the following aural or equally effective landing gear warning devices must be provided:

(1) A device that functions continuously when one or more throttles are closed beyond the power settings normally used for landing approach if the landing gear is not fully extended and locked. A throttle stop may not be used in place of an aural device. If there is a manual shutoff for the warning device prescribed in this paragraph, the warning system must be designed so that when the warning has been suspended after one or more throttles are closed, subsequent retardation of any throttle to, or beyond, the position for normal landing approach will activate the warning device.
(2) A device that functions continuously when the wing flaps are extended beyond the maximum approach flap position, using a normal landing procedure, if the landing gear is not fully extended and locked. There may not be a manual shutoff for this warning device. The flap position sensing unit may be installed at any suitable location. The system for this device may use any part of the system (including the aural warning device) for the device required in paragraph (f)(1) of this section.

Sec. 23.773
Pilot compartment view.

(a) Each pilot compartment must be—
(1) Arranged with sufficiently extensive, clear and undistorted view to enable the pilot to safely taxi, takeoff, approach, land, and perform any maneuvers within the operating limitations of the airplane.
(2) Free from glare and reflections that could interfere with the pilot's vision. Compliance must be shown in all operations for which certification is requested; and
(3) Designed so that each pilot is protected from the elements so that moderate rain conditions do not unduly impair the pilot's view of the flight path in normal flight and while landing.
(b) Each pilot compartment must have a means to either remove or prevent the formation of fog or frost on an area of the internal portion of the windshield and side windows sufficiently large to provide the view specified in paragraph (a)(1) of this section. Compliance must be shown under all expected external and internal ambient operating conditions, unless it can be shown that the windshield and side windows can be easily cleared by the pilot without interruption of normal pilot duties.

Sec. 23.775
Windshields and windows.

…
(f) Unless operation in known or forecast icing conditions is prohibited by operating limitations, a means must be provided to prevent or to clear accumulations of ice from the windshield so that the pilot has adequate view for taxi, takeoff, approach, landing, and to perform any maneuvers within the operating limitations of the airplane.
…

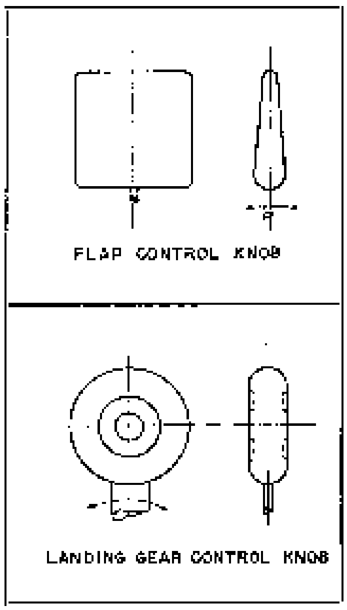
(h) In addition, for commuter category airplanes, the following applies:

…

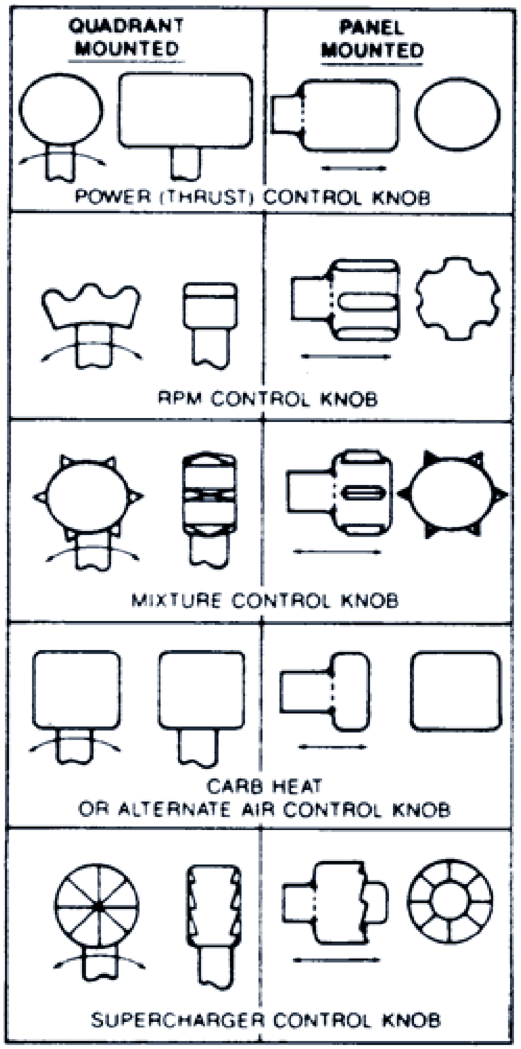
(2) The windshield panels in front of the pilots must be arranged so that, assuming the loss of vision through any one panel, one or more panels remain available for use by a pilot seated at a pilot station to permit continued safe flight and landing.

23.781
Cockpit control knob shape.

(a) Flap and landing gear control knobs must conform to the general shapes (but not necessarily the exact sizes or specific proportions) in the following figure:



(b) Powerplant control knobs must conform to the general shapes (but not necessarily the exact sizes or specific proportions) in the following figure:



23.1303
Flight and navigation instruments.

The following are the minimum required flight and navigation instruments:
(a) An airspeed indicator.
(b) An altimeter.
(c) A direction indicator (nonstabilized magnetic compass).
(d) For reciprocating engine-powered airplanes of more than 6,000 pounds maximum weight and turbine engine powered airplanes, a free air temperature indicator or an air-temperature indicator which provides indications that are convertible to free-air.
(e) A speed warning device for—
(1) Turbine engine powered airplanes; and

(2) Other airplanes for whichVmo/MmoandVd/Mdare established under 23.335(b)(4) and 23.1505(c) ifVmo/Mmois greater than 0.8Vd/Md.
The speed warning device must give effective aural warning (differing distinctively from aural warnings used for other purposes) to the pilots whenever the speed exceeds Vmoplus 6 knots or Mmo+0.01. The upper limit of the production tolerance for the warning device may not exceed the prescribed warning speed. The lower limit of the warning device must be set to minimize nuisance warning;
(f) When an attitude display is installed, the instrument design must not provide any means, accessible to the flight crew, of adjusting the relative positions of the attitude reference symbol and the horizon line beyond that necessary for parallax correction.
(g) In addition, for commuter category airplanes:
(1) If airspeed limitations vary with altitude, the airspeed indicator must have a maximum allowable airspeed indicator showing the variation of V_{MO} with altitude.
(2) The altimeter must be a sensitive type.
(3) Having a passenger seating configuration of 10 or more, excluding the pilot's seats and that are approved for IFR operations, a third attitude instrument must be provided that:
(i) Is powered from a source independent of the electrical generating system;
(ii) Continues reliable operation for a minimum of 30 minutes after total failure of the electrical generating system;
(iii) Operates independently of any other attitude indicating system;
(iv) Is operative without selection after total failure of the electrical generating system;
(v) Is located on the instrument panel in a position acceptable to the Administrator that will make it plainly visible to and usable by any pilot at the pilot's station; and
(vi) Is appropriately lighted during all phases of operation.

23.1305
Powerplant instruments.

The following are required powerplant instruments:
(a) *For all airplanes.* (1) A fuel quantity indicator for each fuel tank, installed in accordance with 23.1337(b).
(2) An oil pressure indicator for each engine.
(3) An oil temperature indicator for each engine.
(4) An oil quantity measuring device for each oil tank which meets the requirements of §23.1337(d).
(5) A fire warning means for those airplanes required to comply with 23.1203.
(b) *For reciprocating engine-powered airplanes.* In addition to the powerplant instruments required by paragraph (a) of this section, the following powerplant instruments are required:
(1) An induction system air temperature indicator for each engine equipped with a preheater and having induction air temperature limitations that can be exceeded with preheat.
(2) A tachometer indicator for each engine.
(3) A cylinder head temperature indicator for—

(i) Each air-cooled engine with cowl flaps;
(ii) [Reserved]
(iii) Each commuter category airplane.
(4) For each pump-fed engine, a means:
(i) That continuously indicates, to the pilot, the fuel pressure or fuel flow; or
(ii) That continuously monitors the fuel system and warns the pilot of any fuel flow trend that could lead to engine failure.
(5) A manifold pressure indicator for each altitude engine and for each engine with a controllable propeller.
(6) For each turbocharger installation:
(i) If limitations are established for either carburetor (or manifold) air inlet temperature or exhaust gas or turbocharger turbine inlet temperature, indicators must be furnished for each temperature for which the limitation is established unless it is shown that the limitation will not be exceeded in all intended operations.
(ii) If its oil system is separate from the engine oil system, oil pressure and oil temperature indicators must be provided.
(7) A coolant temperature indicator for each liquid-cooled engine.
(c) *For turbine engine-powered airplanes.* In addition to the powerplant instruments required by paragraph (a) of this section, the following powerplant instruments are required:
(1) A gas temperature indicator for each engine.
(2) A fuel flowmeter indicator for each engine.
(3) A fuel low pressure warning means for each engine.
(4) A fuel low level warning means for any fuel tank that should not be depleted of fuel in normal operations.
(5) A tachometer indicator (to indicate the speed of the rotors with established limiting speeds) for each engine.
(6) An oil low pressure warning means for each engine.
(7) An indicating means to indicate the functioning of the powerplant ice protection system for each engine.
(8) For each engine, an indicating means for the fuel strainer or filter required by 23.997 to indicate the occurrence of contamination of the strainer or filter before it reaches the capacity established in accordance with 23.997(d).
(9) For each engine, a warning means for the oil strainer or filter required by 23.1019, if it has no bypass, to warn the pilot of the occurrence of contamination of the strainer or filter screen before it reaches the capacity established in accordance with 23.1019(a)(5).
(10) An indicating means to indicate the functioning of any heater used to prevent ice clogging of fuel system components.
(d) *For turbojet/turbofan engine-powered airplanes.* In addition to the powerplant instruments required by paragraphs (a) and (c) of this section, the following powerplant instruments are required:
(1) For each engine, an indicator to indicate thrust or to indicate a parameter that can be related to thrust, including a free air temperature indicator if needed for this purpose.
(2) For each engine, a position indicating means to indicate to the flight crew when the thrust reverser, if installed, is in the reverse thrust position.

(e) *For turbopropeller-powered airplanes.* In addition to the powerplant instruments required by paragraphs (a) and (c) of this section, the following powerplant instruments are required:
(1) A torque indicator for each engine.
(2) A position indicating means to indicate to the flight crew when the propeller blade angle is below the flight low pitch position, for each propeller, unless it can be shown that such occurrence is highly improbable.

23.1309
Equipment, systems, and installations.

…
(b)…
…
(3) Warning information must be provided to alert the crew to unsafe system operating conditions and to enable them to take appropriate corrective action. Systems, controls, and associated monitoring and warning means must be designed to minimize crew errors that could create additional hazards.
(4) Compliance with the requirements of paragraph (b)(2) of this section may be shown by analysis and, where necessary, by appropriate ground, flight, or simulator tests. The analysis must consider—
…
(iv) The crew warning cues, corrective action required, and the crew's capability of determining faults.
…

23.1311
Electronic display instrument systems.

(a) Electronic display indicators, including those with features that make isolation and independence between powerplant instrument systems impractical, must:
(1) Meet the arrangement and visibility requirements of 23.1321.
(2) Be easily legible under all lighting conditions encountered in the cockpit, including direct sunlight, considering the expected electronic display brightness level at the end of an electronic display indictor's useful life. Specific limitations on display system useful life must be contained in the Instructions for Continued Airworthiness required by 23.1529.
(3) Not inhibit the primary display of attitude, airspeed, altitude, or powerplant parameters needed by any pilot to set power within established limitations, in any normal mode of operation.
(4) Not inhibit the primary display of engine parameters needed by any pilot to properly set or monitor powerplant limitations during the engine starting mode of operation.
(5) Have an independent magnetic direction indicator and either an independent secondary mechanical altimeter, airspeed indicator, and attitude instrument or individual electronic display indicators for the altitude, airspeed, and attitude that are independent from the airplane's primary electrical power system. These secondary

instruments may be installed in panel positions that are displaced from the primary positions specified by 23.1321(d), but must be located where they meet the pilot's visibility requirements of 23.1321(a).
(6) Incorporate sensory cues for the pilot that are equivalent to those in the instrument being replaced by the electronic display indicators.
(7) Incorporate visual displays of instrument markings, required by 23.1541 through 23.1553, or visual displays that alert the pilot to abnormal operational values or approaches to established limitation values, for each parameter required to be displayed by this part.
(b) The electronic display indicators, including their systems and installations, and considering other airplane systems, must be designed so that one display of information essential for continued safe flight and landing will remain available to the crew, without need for immediate action by any pilot for continued safe operation, after any single failure or probable combination of failures.
(c) As used in this section, "instrument" includes devices that are physically contained in one unit, and devices that are composed of two or more physically separate units or components connected together (such as a remote indicating gyroscopic direction indicator that includes a magnetic sensing element, a gyroscopic unit, an amplifier, and an indicator connected together). As used in this section, "primary" display refers to the display of a parameter that is located in the instrument panel such that the pilot looks at it first when wanting to view that parameter.

23.1321
Arrangement and visibility.

(a) Each flight, navigation, and powerplant instrument for use by any required pilot during takeoff, initial climb, final approach, and landing must be located so that any pilot seated at the controls can monitor the airplane's flight path and these instruments with minimum head and eye movement. The powerplant instruments for these flight conditions are those needed to set power within powerplant limitations.
(b) For each multiengine airplane, identical powerplant instruments must be located so as to prevent confusion as to which engine each instrument relates.
(c) Instrument panel vibration may not damage, or impair the accuracy of, any instrument.
(d) For each airplane, the flight instruments required by 23.1303, and, as applicable, by the operating rules of this chapter, must be grouped on the instrument panel and centered as nearly as practicable about the vertical plane of each required pilot's forward vision. In addition:
(1) The instrument that most effectively indicates the attitude must be on the panel in the top center position;
(2) The instrument that most effectively indicates airspeed must be adjacent to and directly to the left of the instrument in the top center position;

(3) The instrument that most effectively indicates altitude must be adjacent to and directly to the right of the instrument in the top center position;
(4) The instrument that most effectively indicates direction of flight, other than the magnetic direction indicator required by §23.1303(c), must be adjacent to and directly below the instrument in the top center position; and
(5) Electronic display indicators may be used for compliance with paragraphs (d)(1) through (d)(4) of this section when such displays comply with requirements in §23.1311.
(e) If a visual indicator is provided to indicate malfunction of an instrument, it must be effective under all probable cockpit lighting conditions.

23.1322
Warning, caution, and advisory lights.

If warning, caution, or advisory lights are installed in the cockpit, they must, unless otherwise approved by the Administrator, be—
(a) Red, for warning lights (lights indicating a hazard which may require immediate corrective action);
(b) Amber, for caution lights (lights indicating the possible need for future corrective action);
(c) Green, for safe operation lights; and
(d) Any other color, including white, for lights not described in paragraphs (a) through (c) of this section, provided the color differs sufficiently from the colors prescribed in paragraphs (a) through (c) of this section to avoid possible confusion.
(e) Effective under all probable cockpit lighting conditions.

23.1326 Pitot heat indication systems.

If a flight instrument pitot heating system is installed to meet the requirements specified in 23.1323(d), an indication system must be provided to indicate to the flight crew when that pitot heating system is not operating. The indication system must comply with the following requirements:
(a) The indication provided must incorporate an amber light that is in clear view of a flightcrew member.
(b) The indication provided must be designed to alert the flight crew if either of the following conditions exist:
(1) The pitot heating system is switched “off.”
(2) The pitot heating system is switched “on” and any pitot tube heating element is inoperative.

23.1331 Instruments using a power source.

For each instrument that uses a power source, the following apply:
(a) Each instrument must have an integral visual power annunciator or separate power indicator to indicate when power is not adequate to sustain proper instrument performance. If a separate indicator is used, it must be located so that the pilot using the instruments can

monitor the indicator with minimum head and eye movement. The power must be sensed at or near the point where it enters the instrument. For electric and vacuum/pressure instruments, the power is considered to be adequate when the voltage or the vacuum/pressure, respectively, is within approved limits.

…

23.1335 Flight director systems.

If a flight director system is installed, means must be provided to indicate to the flight crew its current mode of operation. Selector switch position is not acceptable as a means of indication.

23.1337 Powerplant instruments installation.

…

(b) *Fuel quantity indication.* There must be a means to indicate to the flightcrew members the quantity of usable fuel in each tank during flight. An indicator calibrated in appropriate units and clearly marked to indicate those units must be used. In addition:

(1) Each fuel quantity indicator must be calibrated to read "zero" during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under 23.959(a);

…

(d) *Oil quantity indicator.* There must be a means to indicate the quantity of oil in each tank—

(1) On the ground (such as by a stick gauge); and

(2) In flight, to the flight crew members, if there is an oil transfer system or a reserve oil supply system.

Electrical Systems and Equipment

23.1351 General.

…

(c) *Generating system.* There must be at least one generator/alternator if the electrical system supplies power to load circuits essential for safe operation. In addition—

…

(4) There must be a means to give immediate warning to the flight crew of a failure of any generator/alternator.

…

(d) *Instruments.* A means must exist to indicate to appropriate flight crewmembers the electric power system quantities essential for safe operation.

(1) For normal, utility, and acrobatic category airplanes with direct current systems, an ammeter that can be switched into each generator feeder may be used and, if only one generator exists, the ammeter may be in the battery feeder.

(2) For commuter category airplanes, the essential electric power system quantities include the voltage and current supplied by each generator.

…

23.1381 Instrument lights.

The instrument lights must—
(a) Make each instrument and control easily readable and discernible;
(b) Be installed so that their direct rays, and rays reflected from the windshield or other surface, are shielded from the pilot's eyes; and
…
A cabin dome light is not an instrument light.

23.1383 Taxi and landing lights.

Each taxi and landing light must be designed and installed so that:
(a) No dangerous glare is visible to the pilots.
(b) The pilot is not seriously affected by halation.
(c) It provides enough light for night operations.
…

23.1416 Pneumatic de-icer boot system.

If certification with ice protection provisions is desired and a pneumatic de-icer boot system is installed—
…
(c) Means to indicate to the flight crew that the pneumatic de-icer boot system is receiving adequate pressure and is functioning normally must be provided.

23.1419 Ice protection.

If certification with ice protection provisions is desired, compliance with the requirements of this section and other applicable sections of this part must be shown:
…
(d) A means must be identified or provided for determining the formation of ice on the critical parts of the airplane. Adequate lighting must be provided for the use of this means during night operation. Also, when monitoring of the external surfaces of the airplane by the flight crew is required for operation of the ice protection equipment, external lighting must be provided that is adequate to enable the monitoring to be done at night. Any illumination that is used must be of a type that will not cause glare or reflection that would handicap crewmembers in the performance of their duties. The Airplane Flight Manual or other approved manual material must describe the means of determining ice formation and must contain information for the safe operation of the airplane in icing conditions.

23.1431 Electronic equipment.

…

(c) For those airplanes required to have more than one flightcrew member, or whose operation will require more than one flightcrew member, the cockpit must be evaluated to determine if the flightcrew members, when seated at their duty station, can converse without difficulty under the actual cockpit noise conditions when the airplane is being operated. If the airplane design includes provision for the use of communication headsets, the evaluation must also consider conditions where headsets are being used. If the evaluation shows conditions under which it will be difficult to converse, an intercommunication system must be provided.

…

(e) If provisions for the use of communication headsets are provided, it must be demonstrated that the flightcrew members will receive all aural warnings under the actual cockpit noise conditions when the airplane is being operated when any headset is being used.

23.1543 Instrument markings: General.

For each instrument—

(a) When markings are on the cover glass of the instrument, there must be means to maintain the correct alignment of the glass cover with the face of the dial; and

(b) Each arc and line must be wide enough and located to be clearly visible to the pilot.

(c) All related instruments must be calibrated in compatible units.

23.1545 Airspeed indicator.

(a) Each airspeed indicator must be marked as specified in paragraph (b) of this section, with the marks located at the corresponding indicated airspeeds.

(b) The following markings must be made:

(1) For the never-exceed speed V_{NE}, a radial red line.

(2) For the caution range, a yellow arc extending from the red line specified in paragraph (b)(1) of this section to the upper limit of the green arc specified in paragraph (b)(3) of this section.

(3) For the normal operating range, a green arc with the lower limit at V_{S1} with maximum weight and with landing gear and wing flaps retracted, and the upper limit at the maximum structural cruising speed V_{NO} established under 23.1505(b).

(4) For the flap operating range, a white arc with the lower limit at V_{S0} at the maximum weight, and the upper limit at the flaps-extended speed V_{FE} established under 23.1511.

(5) For reciprocating multiengine-powered airplanes of 6,000 pounds or less maximum weight, for the speed at which compliance has been shown with 23.69(b) relating to rate of climb at maximum weight and at sea level, a blue radial line.

(6) For reciprocating multiengine-powered airplanes of 6,000 pounds or less maximum weight, for the maximum value of minimum control speed,

V_{MC}, (one-engine-inoperative) determined under 23.149(b), a red radial line.
(c) If *V* NE or *V* NO vary with altitude, there must be means to indicate to the pilot the appropriate limitations throughout the operating altitude range.
(d) Paragraphs (b)(1) through (b)(3) and paragraph (c) of this section do not apply to aircraft for which a maximum operating speed *V* MO/ *M* MO is established under 23.1505(c). For those aircraft there must either be a maximum allowable airspeed indication showing the variation of *V* MO/ *M* MO with altitude or compressibility limitations (as appropriate), or a radial red line marking for *V* MO/ *M* MO must be made at lowest value of *V* MO/ *M* MO established for any altitude up to the maximum operating altitude for the airplane.

23.1549 Powerplant and auxiliary power unit instruments.

For each required powerplant and auxiliary power unit instrument, as appropriate to the type of instruments—
(a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line;
(b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits;
(c) Each takeoff and precautionary range must be marked with a yellow arc or a yellow line; and
(d) Each engine, auxiliary power unit, or propeller range that is restricted because of excessive vibration stresses must be marked with red arcs or red lines.

23.1551 Oil quantity indicator.

Each oil quantity indicator must be marked in sufficient increments to indicate readily and accurately the quantity of oil.

23.1553 Fuel quantity indicator.

A red radial line must be marked on each indicator at the calibrated zero reading, as specified in 23.1337(b)(1).

23.1555 Control markings.

(a) Each cockpit control, other than primary flight controls and simple push button type starter switches, must be plainly marked as to its function and method of operation.
(b) Each secondary control must be suitably marked.
(c) For powerplant fuel controls—
(1) Each fuel tank selector control must be marked to indicate the position corresponding to each tank and to each existing cross feed position;
(2) If safe operation requires the use of any tanks in a specific sequence, that sequence must be marked on or near the selector for those tanks;

(3) The conditions under which the full amount of usable fuel in any restricted usage fuel tank can safely be used must be stated on a placard adjacent to the selector valve for that tank; and
(4) Each valve control for any engine of a multiengine airplane must be marked to indicate the position corresponding to each engine controlled.
(d) Usable fuel capacity must be marked as follows:
(1) For fuel systems having no selector controls, the usable fuel capacity of the system must be indicated at the fuel quantity indicator.
(2) For fuel systems having selector controls, the usable fuel capacity available at each selector control position must be indicated near the selector control.
(e) For accessory, auxiliary, and emergency controls—
(1) If retractable landing gear is used, the indicator required by 23.729 must be marked so that the pilot can, at any time, ascertain that the wheels are secured in the extreme positions; and
(2) Each emergency control must be red and must be marked as to method of operation. No control other than an emergency control, or a control that serves an emergency function in addition to its other functions, shall be this color.

Sec. 91.205
Powered civil aircraft with standard category U.S. airworthiness certificates: Instrument and equipment requirements.

(a) *General.* Except as provided in paragraphs (c)(3) and (e) of this section, no person may operate a powered civil aircraft with a standard category U.S. airworthiness certificate in any operation described in paragraphs (b) through (f) of this section unless that aircraft contains the instruments and equipment specified in those paragraphs (or FAA-approved equivalents) for that type of operation, and those instruments and items of equipment are in operable condition.
(b) *Visual-flight rules (day).* For VFR flight during the day, the following instruments and equipment are required:
(1) Airspeed indicator.
(2) Altimeter.
(3) Magnetic direction indicator.
(4) Tachometer for each engine.
(5) Oil pressure gauge for each engine using pressure system.
(6) Temperature gauge for each liquid-cooled engine.
(7) Oil temperature gauge for each air-cooled engine.
(8) Manifold pressure gauge for each altitude engine.
(9) Fuel gauge indicating the quantity of fuel in each tank.
(10) Landing gear position indicator, if the aircraft has a retractable landing gear.
…

(d) Instrument flight rules. For IFR flight, the following instruments and equipment are required:
(1) Instruments and equipment specified in paragraph (b) of this section, and, for night flight, instruments and equipment specified in paragraph (c) of this section.
(2) Two-way radio communications system and navigational equipment appropriate to the ground facilities to be used.
(3) Gyroscopic rate-of-turn indicator, except on the following aircraft:
(i) Airplanes with a third attitude instrument system usable through flight attitudes of 360 degrees of pitch and roll and installed in accordance with the instrument requirements prescribed in Sec. 121.305(j) of this chapter; and
(ii) Rotorcraft with a third attitude instrument system usable through flight attitudes of ±80 degrees of pitch and ±120 degrees of roll and installed in accordance with Sec. 29.1303(g) of this chapter.
(4) Slip-skid indicator.
(5) Sensitive altimeter adjustable for barometric pressure.
(6) A clock displaying hours, minutes, and seconds with a sweep-second pointer or digital presentation.
(7) Generator or alternator of adequate capacity.
(8) Gyroscopic pitch and bank indicator (artificial horizon).
(9) Gyroscopic direction indicator (directional gyro or equivalent).
(e) *Flight at and above 24,000 ft. MSL (FL 240).* If VOR navigational equipment is required under paragraph (d)(2) of this section, no person may operate a U.S.-registered civil aircraft within the 50 states and the District of Columbia at or above FL 240 unless that aircraft is equipped with approved distance measuring equipment (DME). When DME required by this paragraph fails at and above FL 240, the pilot in command of the aircraft shall notify ATC immediately, and then may continue operations at and above FL 240 to the next airport of intended landing at which repairs or replacement of the equipment can be made.
(f) *Category II operations.* The requirements for Category II operations are the instruments and equipment specified in—
(1) Paragraph (d) of this section; and
(2) Appendix A to this part.
(g) *Category III operations.* The instruments and equipment required for Category III operations are specified in paragraph (d) of this section.
(h) *Exclusions.* Paragraphs (f) and (g) of this section do not apply to operations conducted by a holder of a certificate issued under part 121 or part 135 of this chapter.

(3) Flight Course Outline. (i) The flight training curriculum must include at least 10 hours of flight instruction in an airplane specified in §63.37(a). The flight time required for the practical test may not be credited as part of the required flight instruction.
(ii) All of the flight training must be given in the same type airplane.
(iii) As appropriate to the airplane type, the following subjects must be taught in the flight training course:
SUBJECT

RECOGNITION AND CORRECTION OF IN-FLIGHT MALFUNCTIONS

To include:
Analysis of abnormal engine operation.
Analysis of abnormal operation of all systems.
Corrective action.